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A 25-ton mobile crane transporting prefabricated sections to a ship under construction in the Kingston Yard of Messrs. Lithgows Limited, Port Glasgow, where 'English Electric' A.C. arc welding plant is extensively used

Modern Building Methods Using Welding in a Clyde Shipyard

By J. THOM, Glasgow Branch Office.

THE SHIPBUILDERS WHOSE yards range on both banks of the River Clyde have always been pioneers and are ever in the forefront with new ideas and new methods.

Before the Second World War the British Merchant Navy was much below the safety mark in numbers of ships, and many of these ships were very old. A very large programme of building was started, but it quickly became necessary to introduce new methods to reduce the time taken for construction. D.C. electric welding had been in use since about 1920, mostly for welding pipe flanges and other minor work in the plumbers' shop. Riveting was still the method used to 'join' sections and plates, and hand, pneumatic and hydraulic riveters were in use for this work. About 1925 it became increasingly difficult to get skilled riveters, and because of this hydraulic riveting was brought into use. A very good rivet is formed in a hydraulic machine under a pressure of 30 tons, and the manipulation of the machine does not call for such skill as is required for the other methods. This machine, however, can mostly only be used for fabrication in the sheds.

To speed-up construction it was obvious that welding should play a greater part, but current for D.C. welding had to be supplied from rotating plant and resistances, which were costly and difficult to obtain ; the maintenance and distribution problems also were considerable. A.C. welding was therefore adopted and eventually sponsored by the Admiralty. By 1935 many yards were equipped with a large amount of A.C. welding plant using static transformers and oil-filled regulators.

During the war ships were lost faster than they were built, so that at the end of the war the need for tankers, particularly, was great. The construction of the oil-carrying type of ship allowed a very great deal of welding to be done, so that its use grew until practically the whole vessel was of welded construction, except perhaps the shell where seams were riveted. With rising costs of labour and raw materials which seemed likely to limit the number of vessels which owners could afford to have built, and increasing foreign competition, it became essential to reduce the time taken from laying the keel-plate to launching and, for the first time, the time-honoured fundamental method of construction was critically examined. In most other industries prefabrication was playing its part in speeding-up manufacture, and the shipyards also turned to this as a possible solution to their problem.

The shipyard chosen to illustrate this article is the Kingston Yard of Messrs. Lithgows Limited, at Port Glasgow. Many other yards, some large, some small, have introduced prefabrication to a very great extent, but few have changed the old-established first principles of shipbuilding. In Kingston Yard traditional methods have been changed in a most courageous way, and the new technique evolved has been so successful in reducing the time taken to build a ship that the following comparison of the old and new methods may be of interest, together with a general description of the electrical equipment employed. The first A.C. welding plant introduced into this yard in 1934 was made by The English Electric Company, and included this company's first oil-filled welding regulator. Some 40 transformers and 200 regulators are now in use, all of 'English Electric' manufacture.

Older Method of Ship Construction

The first operation when building a ship is traditionally to lay the keel plates the whole length,

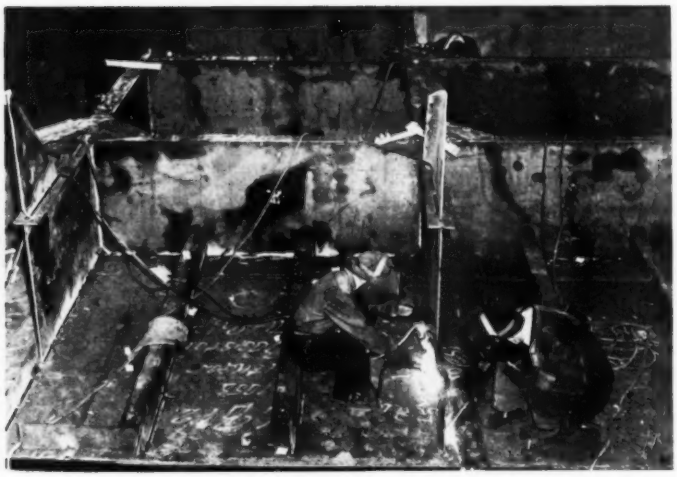


Fig. 1. *Welding a section of a ship in the prefabrication shop*

and from this base the ship grows until the deck plates are reached evenly.

In a tanker the next operation is to lay the centre tank all along the keel and, as this type of ship is generally split up into three separate systems of tanks, the two outer or port and starboard tanks are then added to the centre tank and the structure rises evenly up to the main deck. During the last war welding was used increasingly for joining plates, brackets, girders, etc., instead of riveting, but most if not all of the welding had to be done on the building berths. There are inherent disadvantages in this method, and the salient points are :—

(*a*) It is most difficult to supervise construction over the whole length of the ship, which might be 500 feet long, and this is particularly so where small sections have to be joined in awkward and hidden places.

(*b*) Much of the welding has to be done positionally ; vertical and overhead welding is of necessity slower than downhand welding, and the skill of the welder must be of a high order to ensure the same class of weld.

(*c*) The general overall construction of the ship is slow for the reasons stated in (*a*) and (*b*), and also because a large amount of hand-fitting must be done on the internal structure.

(*d*) During the fitting of the tanks on the keel the whole honeycomb is open, so that welding work must stop during inclement weather.

The average time taken to build an oil tanker, using the traditional methods, was five months longer from laying the keel to launching the hull than is now required with the following new method.

New Method of Ship Construction

After much careful thought, the management of Kingston Yard redesigned or adapted the design of ships to suit their novel method of building.

The ship is now designed in such a way that it can be built in prefabricated sections using a combination of hydraulic riveting and welding, and for easy handling and assembly each section is limited to 25 tons in weight. Specially designed mobile cranes running on precision-laid track (Frontispiece) transport the sections to the berths as required, a careful check being kept to ensure that too many finished sections do not occupy useful space.

The 25-ton sections are all prepared under cover where it is easy for the welders to work (Fig. 1) ; some sections are all-welded and others are a combination of hydraulic riveting and welding.

No attempt is made to lay the whole keel plate, but the ship grows in complete units from stern to bow, each unit consisting of prefabricated sections which only require to be assembled and welded together on the open berths. Each unit is completely assembled up to the deck plates.

Fig. 2 shows in section how the outer shell is dealt with, the build-up of one unit comprising :—

1. The bottom shell or keel plate.
2. The bilges, port and starboard.
3. The side shells, port and starboard.
4. The deck.

The first section of the first unit assembled is at the stern and consists of the engine room seating.

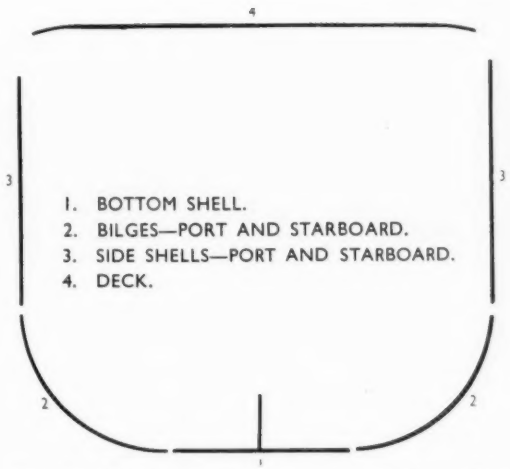


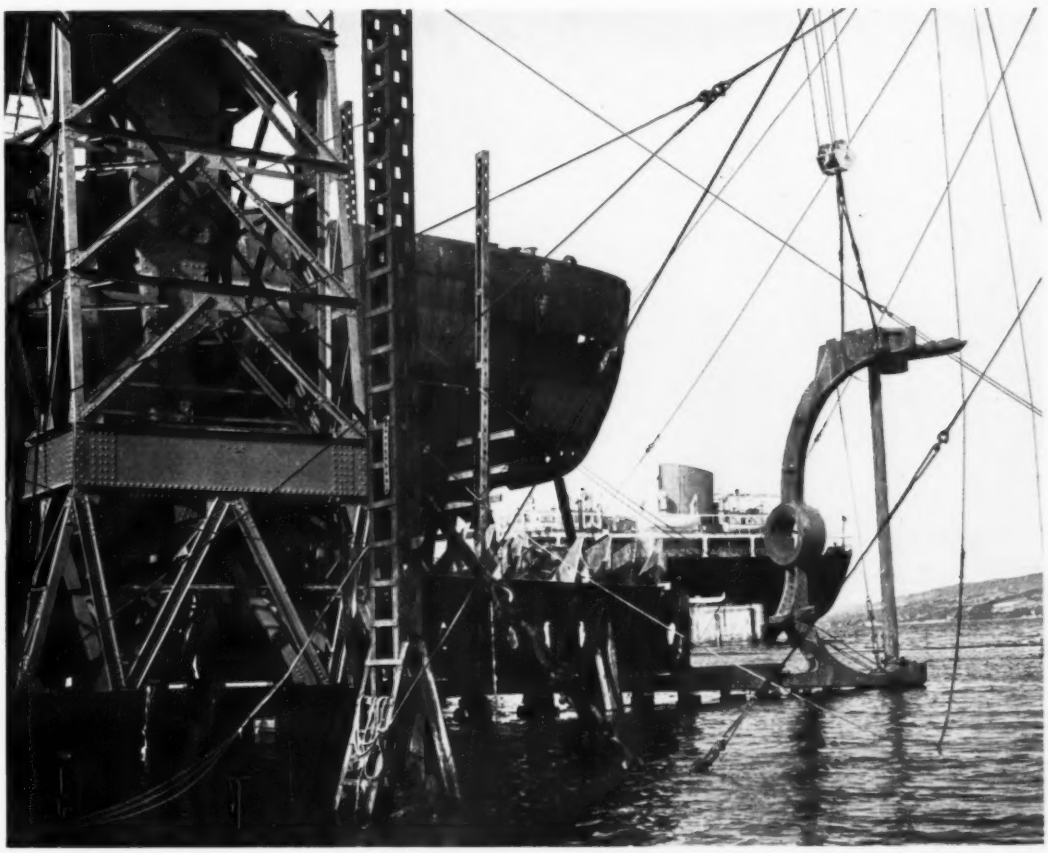
Fig. 2. Diagrammatic cross-section of a ship, showing how the outer shell is built up

This structure is a piece of the keel and forms the aft part of the ship on which is built a conventional stern. Fig. 3 shows this operation taking place, and the first stern unit is also nearing completion.

It is interesting to note from Figs. 4 and 8 that it is not necessary to arrange for a steady growth of units from the original stern unit to the bow. It often happens that the material available and the position in the prefabrication shops make it easier to finish sections which are not immediately required. The units formed by those sections can by careful alignment be assembled on the berth and the gaps closed later.

Much ingenuity and careful planning were applied

Fig. 3. Building the stern of a tanker



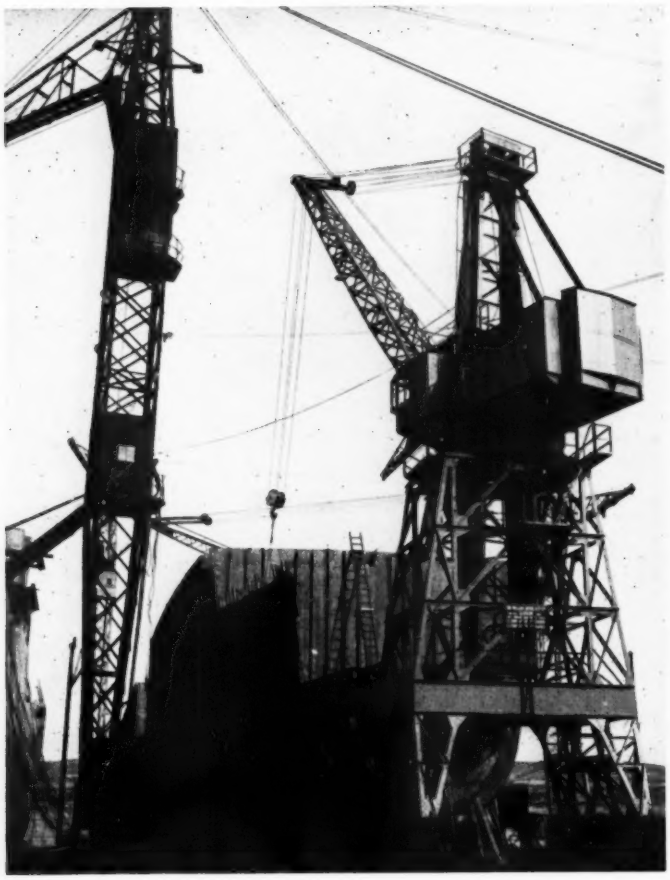


Fig. 4. A prefabricated side plate in position ready for fixing

to evolve this rather revolutionary system of building a tanker, and some of the difficulties which were overcome are now considered.

Shop Handling

The conventional way of handling large sections in a shop is by overhead travelling crane. This requires high roofs with strong columns and girders. In the years just after the last war the time required for the delivery of structural steelwork, cranes etc. was very long. The existing shops were low-roofed and generally the buildings were entirely unsuitable for the installation of cranes.

As the need for ships was great, Messrs. Lithgows decided not to wait for overhead shop cranes ; instead, four-wheeled bogie trucks were designed with flat tops each suitable for carrying a 25-ton section. The welding of these sections is done on specially designed steel trestles, and the assembling of the plates and erections is handled by the existing 3/5-ton cranes. The trucks are fitted with a jack at each of the four corners of the flat steel top and are manoeuvred into position under the section to be lifted. The jacks are operated until the section is lifted clear of the trestles and the bogie is then drawn away with its load by a 24 h.p. petrol-engined tractor. The bogies and the trestles were all designed and built completely in Messrs. Lithgows own works.

The trestles, bogies, and the type of tractor used are shown in Figs. 5, 6 and 7. To allow clearance for these large sections to be moved out of the prefabrication shops, all electrical gear, including welding transformers, is raised above ground level as shown in Fig. 5.

Building Berths

The normal shipbuilding berth has an ordinary soil base, and this is of course not suitable to support bogies carrying 25-ton weights nor tractors exerting heavy pulls. The berths, and all approach roads to them, were therefore concreted right down to the water edge. The long lines of columns which normally support planks and gangways during the construction of a ship are not necessary and have been eliminated, and this gives the building berths a rather unusual appearance.

Handling at the Berths

The special 25-ton travelling cranes built to

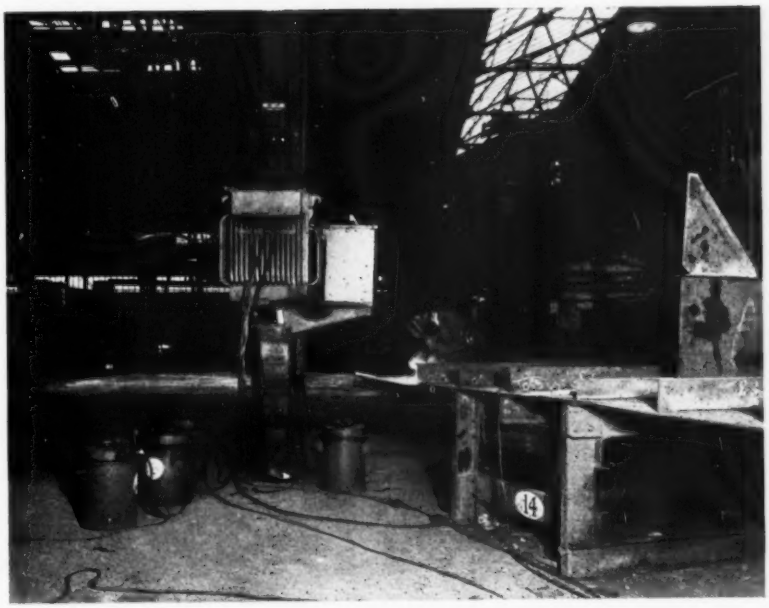


Fig. 5. Welding a section on the special trestles used to facilitate removal by bogie trucks

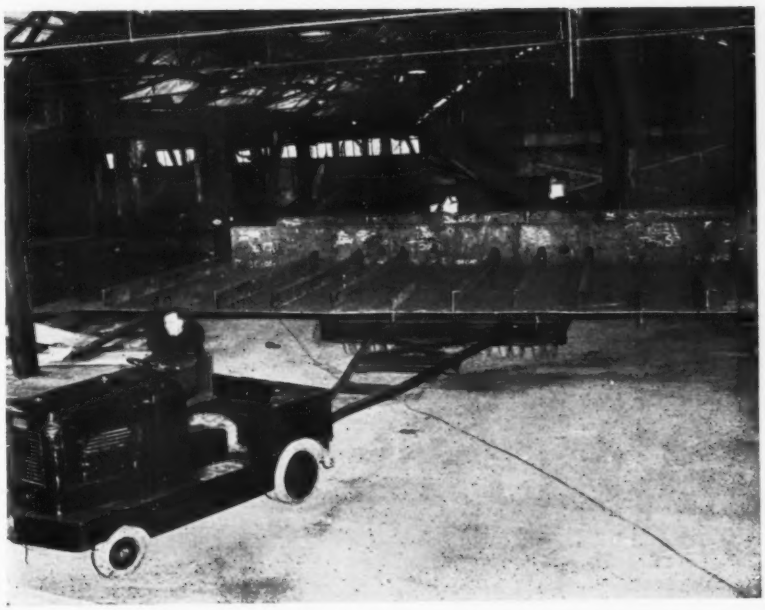


Fig. 6. Part of a welded bulkhead being transported to the berth

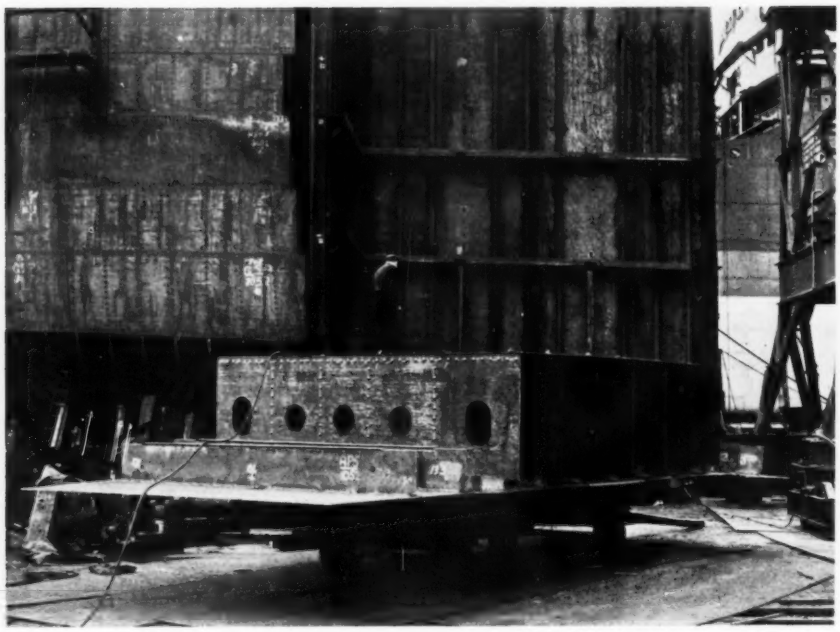


Fig. 7. A prefabricated section waiting to be lifted into position on a tanker

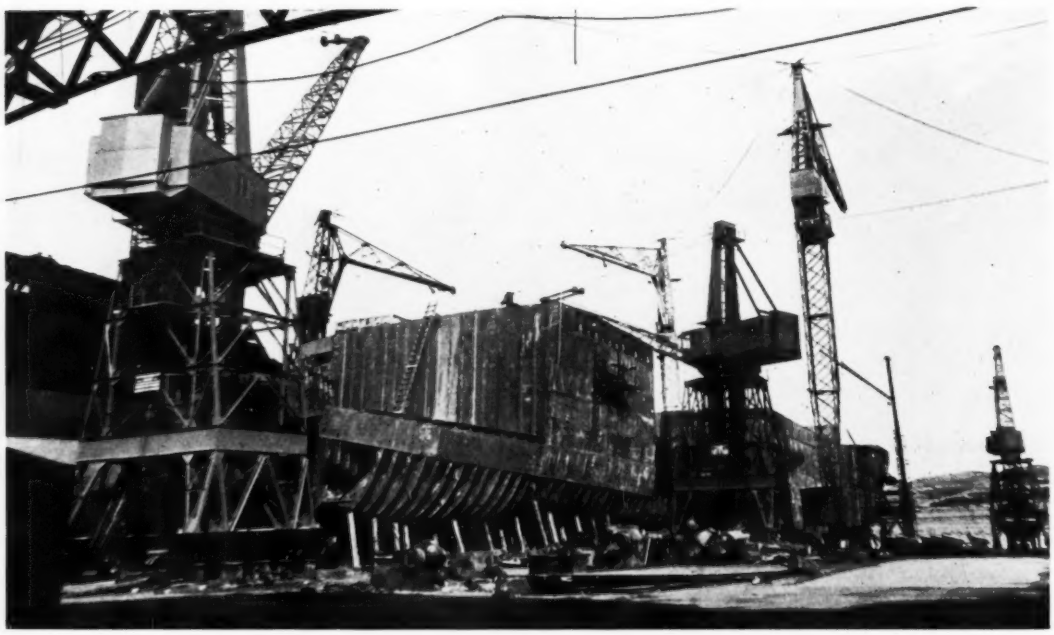


Fig. 8. A tanker of about 13,000 tons being built

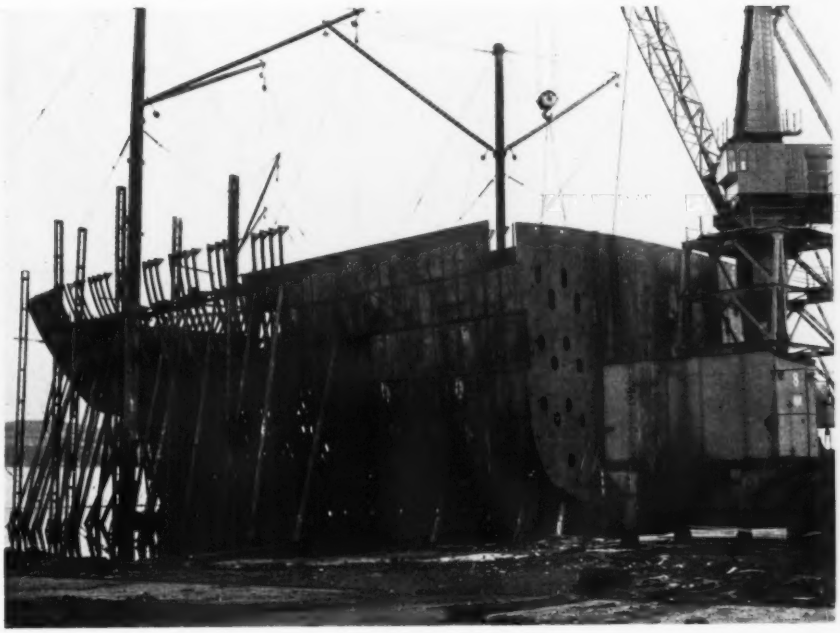


Fig. 9. The stern of a tanker during construction, with metal house for welding transformers and switchgear in the foreground

handle the sections and place them in position for assembly and welding together, normally run on rails laid in the concrete. The four wheels are so designed, however, that when a crane becomes 'boxed in' between units which have been built forward and aft, the whole crane structure can be jacked up, the wheels turned at right angles to the rails, and the crane pulled to the side so that the gap between units can be closed. Fig. 8 shows a ship being built with the crane at the bow in line, whereas the crane working nearer the stern has been moved out to the side.

Lining-up the Prefabricated Sections

A serious problem which had to be faced with this method of construction was how to ensure correct alignment from stern to bow of each section as it was joined to the structure. It was solved with considerable ingenuity. Civil engineers were called in to lay the travelling crane rails which, of course, run the whole length of each berth. These rails are exactly equidistant about the centre-line of the berth so that it is easy at any time to line up the sections on these rails as the ship grows.

Welding Plant

When A.C. welding on a large scale was first introduced into the Kingston Yard, practically all welding was done on the building berths. Metal houses were therefore constructed on both sides of each berth to house the necessary control switchgear, welding transformers and the capacitors for power-factor correction. A typical house is shown in the foreground of Fig. 9 and, as will be seen, these houses are built on supports to allow passageway beneath. The interior of a typical house is shown in Fig. 10. The switchboard consists of a standard metalclad busbar chamber with incoming isolator and outgoing H.R.C. fuse-switches feeding the welding transformers. The transformers are for six and twelve operators, with a rating of 300 amp per operator. Fed from the transformers are 300-amp and 400-amp welding regulators of sufficient number to allow up to 50 men to work on two adjacent berths. It is interesting to note that most of the plant is 18 years old and has given, and is giving, trouble-free service. Because of their situation, none of the original transformers has ever had its oil changed. The original installation included 300-amp (maximum) regulators, but

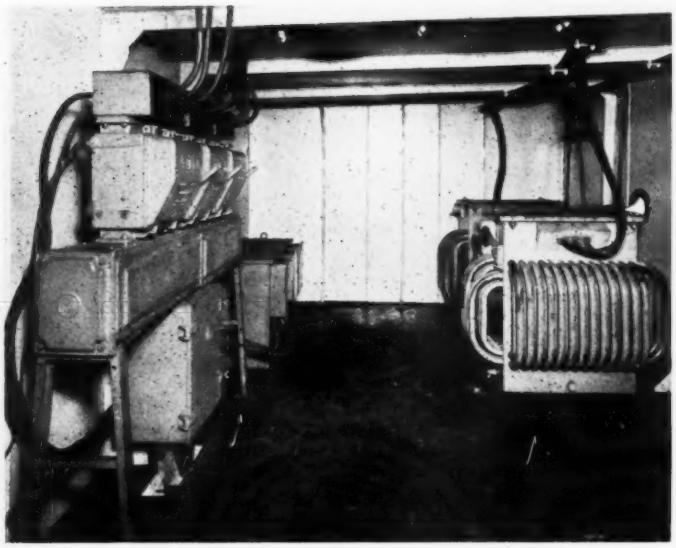


Fig. 10. *Interior of a typical shipyard welding transformer station*

to cater for the increasing use of larger electrodes and those of the deep penetration type, all the regulators recently supplied are of the 400-amp size.

In the prefabrication shops, which were equipped recently, 'English Electric' 12-operator transformers, giving 300 amp per man, were adopted as a standard and were mounted on platforms supported from the roof columns as in Fig. 5, the platform being large enough to take the attendant capacitor. A 300-amp H.R.C. fuse-switch is mounted on the column below each transformer to control the 440-volt input. As will be seen, the 400-amp regulators are normally grouped round the transformer. The transformers are so placed to allow welding to go on all over the shop floor, and the present capacity is installed for a maximum of 60 men.

Two 'English Electric' rectified A.C. automatic stud welding plants are provided in the Yard, and being portable they can be taken to any of the berths as required. The ignitron banks for these are placed in the berth transformer houses beside a transformer, which is then exclusively used to supply the stud welding set. This is most important as it has been found that the current peak as each stud is welded (using $\frac{1}{2}''$ diameter deck studs) is over 400 amp on the 100-volt side. These peaks are very frequent when a large area of deck has to be studded, and if ordinary welding regulators are connected to the same transformer, poor welds result. It is also essential to have the ignitron bank connected to the 100-volt output side of the transformer with the shortest leads possible, as a small voltage drop in these seriously affects the stud welding operation. The man doing the actual welding with the gun, however, can be 300 feet away from the ignitron bank and can still weld-on $\frac{1}{2}''$ diameter studs quite successfully.

Fig. 11. *The original* 440 *volts main switchboard, with H.R.C. fuse-switch extension on the right*

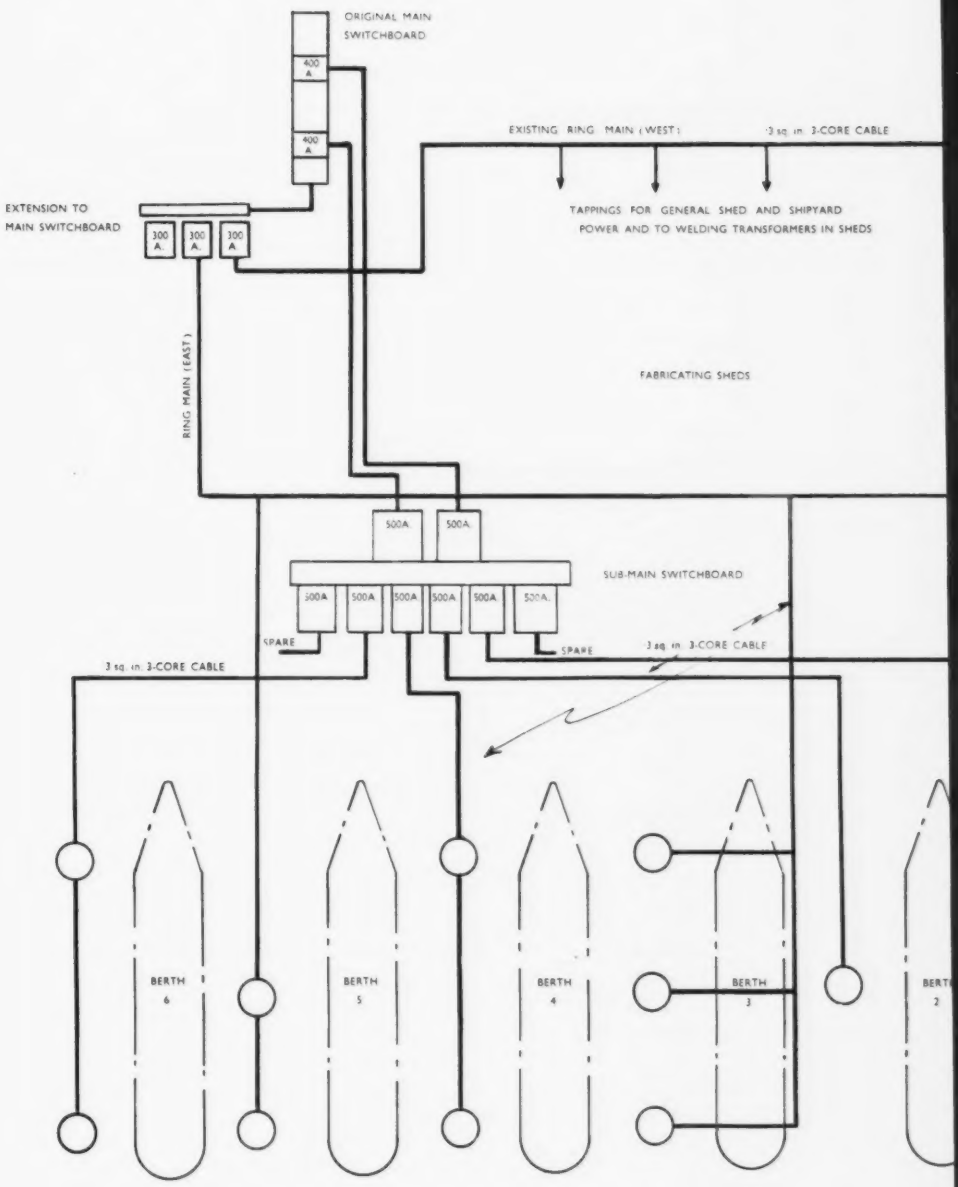
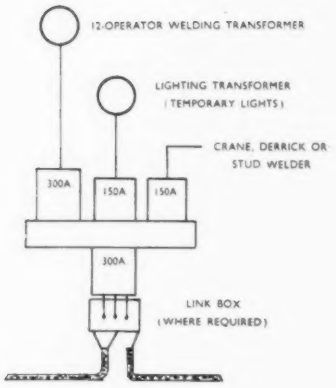


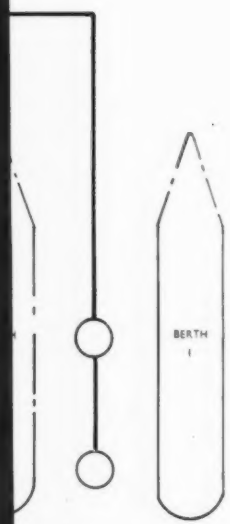
Fig. 12. Schematic diagram of t



TYPICAL WELDING TRANSFORMER HOUSE CIRCUITS

NOTE

○ INDICATES THE WELDING TRANSFORMER HOUSES AT BERTHS



...e main electrical system

Electrical Distribution System

Alternating current at 440 volts, 25 cycles, 3-phase, was first introduced into the Yard in 1929, and the original 'English Electric' main switchboard of the conventional 'sindanyo' panel type with back-of-board oil circuit-breakers is still in service, although to accommodate the latest additional welding plant an extension by means of an H.R.C. fuse-switchboard has recently been installed (Fig. 11). A schematic diagram of connections is shown in Fig. 12 from which it will be seen that the system of ring main distribution originally planned in 1929 has been expanded and altered to suit the increase in welding load.

The completely new shipbuilding technique was planned and organised with small capital expenditure on buildings and plant, and the same can be said of the electrical distribution system, which was altered and adapted at low cost to supply the new yard layout.

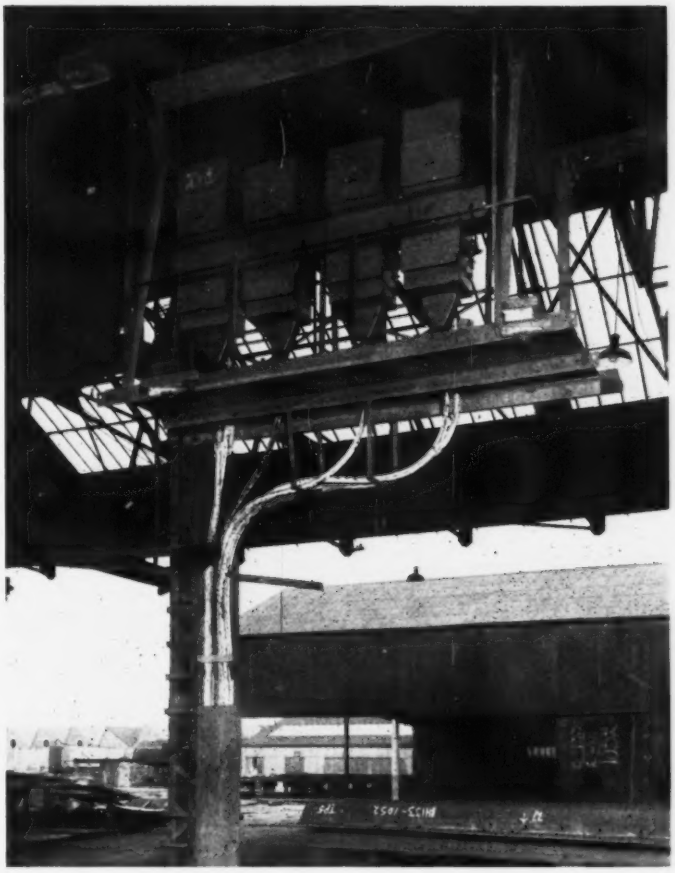


Fig. 13. *Main distribution board for feeding welding transformers*

The average maximum demand in the Yard is 1,500 kW, and of this the welding plant accounts for 1,000 kW. Every welding transformer has its own capacitor for power factor improvement, usually fitted adjacent to it, and some of the larger motors such as those driving the compressors also have capacitors connected directly across their terminals. In addition, to achieve as nearly as possible unity power factor, 'topping up' capacitors are connected to the main switchboard busbars. It is interesting to note here that the practice which has commonly prevailed up to now of providing a capacitor for each welding transformer has proved troublesome at times of light load or no load. The operators are not in a position to switch off the transformers, and in consequence it is possible to have, say, 20 transformers each with a 30 kVAr capacitor in circuit but without load. The result is a very heavy reactive leading kVA loading on cables and main power transformers. In yards where the number of welding transformers used is steadily increasing, a point can be reached where this reactive kVA can become excessive. The solution would seem to be to transfer some of the capacitors into the main substation and connect them to the busbars of the main switchboard, but provide fully automatic control so that they are switched in and out in single or multiple units as the load varies.

Conclusion

No attempt has been made to discuss in any technical detail either welding technique or the electrical system, the intention being to describe a new shipbuilding method, still expanding and developing, in which 'English Electric' welding plant has been used exclusively. It is a tribute to the planning of the original electrical system by the engineers of Messrs. Lithgows and The English Electric Company, that it has permitted fairly extensive re-organisation at so little cost and with a minimum of alteration to the switchgear and cabling.

Acknowledgement is made to the Directors of Messrs. Lithgows Limited for their permission to publish this article, and to the members of the firm's staff whose assistance contributed to its preparation.

The new building methods were introduced under the guidance of Mr. John Morton and the late Sir James and Mr. Henry Lithgow.

The Napier 'Nomad' Compound Diesel Aero Engine

THE 'NOMAD' WAS designed to provide an aero engine having the lowest possible fuel consumption under any operating conditions. This was achieved by compounding the simplest form of two-stroke diesel engine with a gas turbine, and transmitting the power through a propeller. This type of engine also enables a wide range of fuels to be used, such as diesel fuel, kerosene and wide-cut gasoline. The low fuel consumption (as compared with a gas turbine, used either for driving a propeller or as a jet engine) is achieved by the use of a high compression ratio, and a high expansion ratio, which is made possible by the combination of the diesel engine with a gas turbine. In the ordinary turbo-jet engine the compression and expansion ratios are lower, resulting in a higher fuel consumption.

The Nomad, of which two views are shown in Figs. 1 and 2, consists of a simple valveless two-stroke diesel engine to which is added a turbine-compressor set. The axial-flow compressor is on a common shaft with a multi-stage exhaust turbine, and the turbine-compressor set thus formed is coupled mechanically to the compression-ignition engine through gearing. The power of the compression-ignition engine and the surplus power available from the exhaust gas turbine are transmitted to a common single-rotation propeller shaft by a reduction gear in the nose of the engine assembly. The length of the engine is 9 feet 11 inches and the frontal area of the power plant 19·25 square feet. The Nomad is controlled by a single pilot's lever.

Chief Characteristics

The chief characteristics of the Nomad are :—

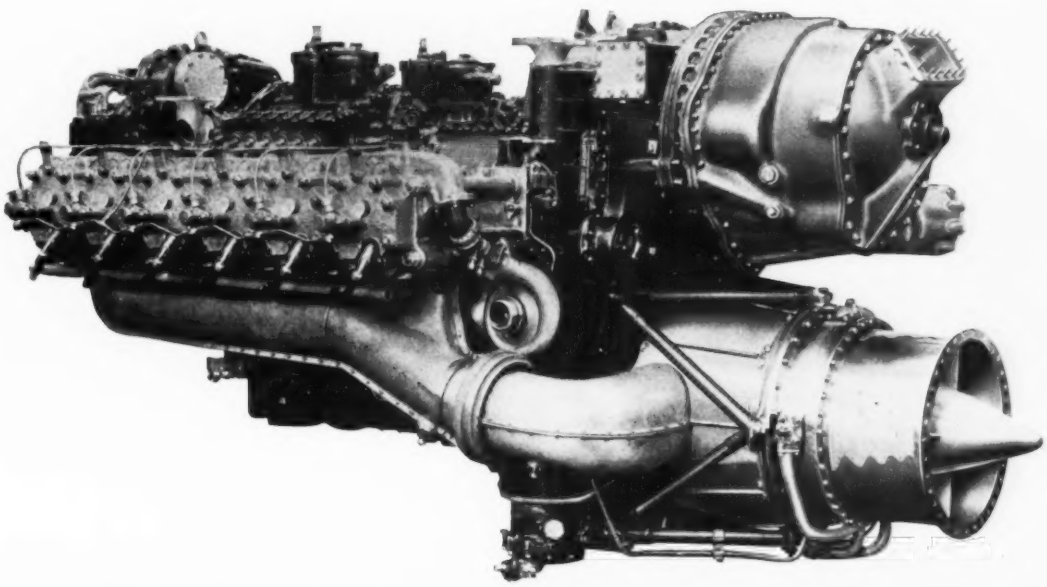


Fig. 1. *Napier 'Nomad'* 3,135 *e.h.p. compound diesel engine, from turbine end*

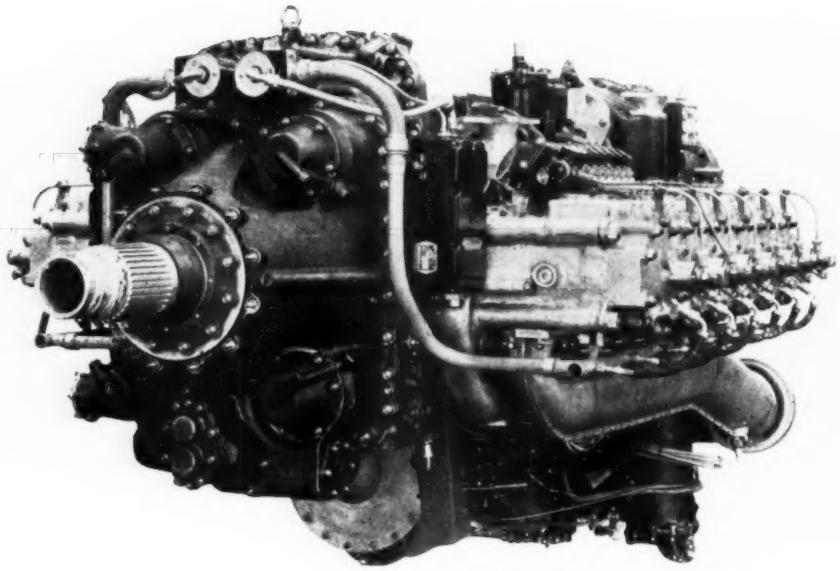


Fig. 2. Napier 'Nomad' 3,135 e.h.p. compound diesel engine, from propeller end

(*a*) *Low specific fuel consumption* over a wide range of altitudes and speeds ; this remains between ·33 and ·35 lb/e.h.p.-hr.

(*b*) *Choice of fuels*—the engine operates equally efficiently on kerosene, diesel fuel or wide-cut gasoline.

(*c*) *Insensitivity to atmospheric temperature* compared with propeller turbine or turbo-jet aero-engines.

(*d*) *Weight*—3,580 lb for an e.h.p. of 3,135.

(*e*) *Simplicity*—the engine consists of a valve-less two-stroke diesel engine in its simplest form, to which has been added a normal type of turbine and compressor of small overall dimensions.

(*f*) *Economy*—The low fuel consumption, apart from providing an enormous economy in fuel consumed, also reduces the proportion of aircraft all-up weight which must be utilised for fuel, including reserves, and thus permits the carriage of a given payload over a given range in an aeroplane of smaller size than would be required with turbo-jet engines whose specific fuel consumption would be at least twice as great as that of the Nomad.

The Nomad is ideally suited for operation over short or long sectors, at any altitude convenient to the operator, where large carrying capacity is required.

The information which follows compares the relative performance of three hypothetical aircraft ; one powered by four turbo-jet engines of 10,000 lb sea level static thrust, one by four propeller turbines of 3,780 e.h.p. for take-off, and one by four Nomad engines of 3,135 e.h.p. for take-off. The all-up weight of each aircraft is different, but the same payload can be carried by each over a still air sector distance of 2,860 statute miles.

Aircraft Data	Nomad	Prop-turbine	Turbo-jet
Take-off power ..	12,540 e.h.p.	15,120 e.h.p.	40,000 lb thrust
Span, feet	132	140	123·5
Wing area (gross) square feet ..	1,840	2,050	2,185
Aspect ratio	9·5	9·5	7·0
Length (overall), feet	114	114	114
Fuselage diameter, feet	12	12	12
Volumetric capacity payload, pounds ..	25,000	25,000	25,000
Aircraft basic equipped weight, pounds ..	71,000	70,000	70,370

Aircraft all-up weight, pounds		123,500	140,000	153,000

The all-up weight of each aircraft is different, but the same payload can be carried by each over a still-air sector distance of 2,860 statute miles.

Aircraft Size

The extremely low fuel consumption of the Nomad compared with propeller turbine and pure turbo-jet engines is such that for long range operations, such as 2,860 statute miles sector distance, the same payload can be carried in a much smaller aeroplane when powered by Nomads than when propeller turbines or pure turbo-jets are used.

Since the aircraft cost is approximately proportional to equipped airframe weight, the low fuel consumption of the Nomad not only provides economy through the smaller quantity of fuel consumed in carrying a given payload for a given distance, but it also permits a great economy in the size, and hence the cost, of the vehicle required to perform the operation. This is graphically illustrated in Fig. 3.

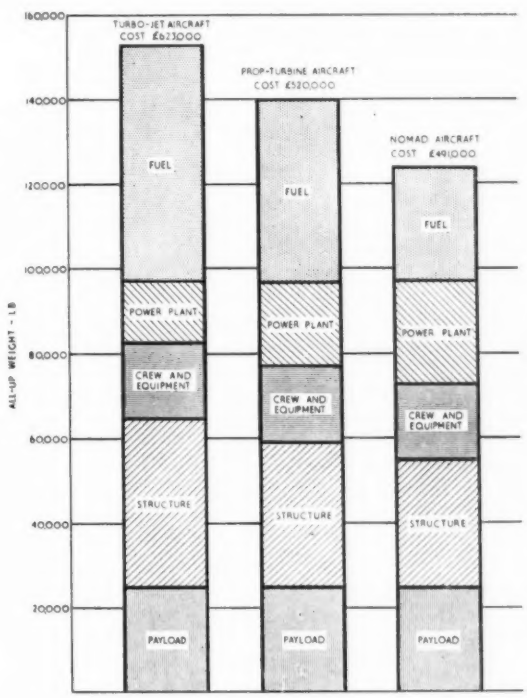


Fig. 3. All-up weight and cost of aircraft for a given duty—25,000 lb of payload over a still-air sector distance of 2,860 statute miles

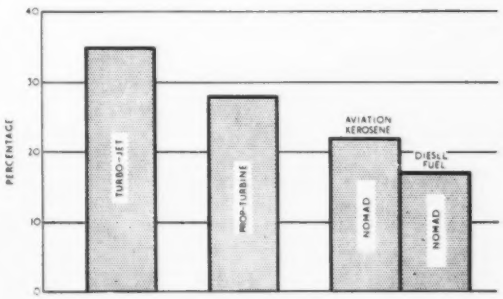


Fig. 4. Fuel cost as a percentage of direct operating costs

Economic Effect of Fuel Consumption

Fuel cost is the largest individual item in the direct operating costs of an aeroplane. No matter what developments are introduced by the aircraft designers, engines will always consume fuel. It is possible for an airline operator to reduce every operating cost except that of the fuel consumption of his power plants, for here he is entirely in the hands of the engine designer. For a given capacity payload and range an aircraft's earning efficiency is impaired by all contingencies for which allowances have to be made, such as head winds, navigational errors, holding time, and diversions. The lower the specific fuel consumption of the engines and the cheaper the fuel consumed, the lower will be the direct operating cost.

Fig. 4 shows the striking difference in fuel cost between the Nomad, the propeller turbine, and turbo-jet, expressed as a percentage of the direct operating cost. The effect of these fuel costs when operating on the London-Bahrein sector (3,150 miles) is shown in Fig. 5. To obtain the cost per passenger mile, the weight of one passenger plus baggage has been taken at 230 lb.

Effect of Fuel Reserves on Payload

The effect of fuel reserves on payload is shown in Fig. 6, where with the aircraft operating on the London-Bahrein sector, the fuel reserves on the

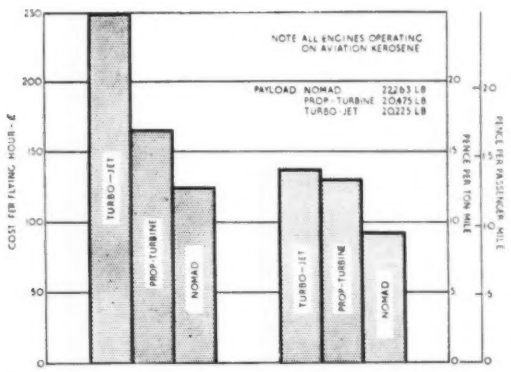


Fig. 5. Direct operating costs for London-Bahrein sector (3,150 *statute miles*)

Nomad aircraft amount to only 14% of the capacity payload, against 24% for the propeller turbine aircraft, and 37% for the turbo-jet aircraft.

Fig. 7 shows the cost of these fuel reserves, and the cost of the total fuel carried by the three aircraft. For the sector considered (London-Bahrein) the propeller turbine aircraft uses 62% more fuel than the Nomad aircraft, and the turbo-jet aircraft uses 120% more than the Nomad aircraft, when each aircraft is running on aviation kerosene fuel. Running the Nomad on diesel fuel further increases this advantage as shown.

Advantages of Long Range

The advantages of long range are many. In the first place, it permits regularity of operation against a wide variety of head winds and weather conditions. Secondly, it is of great benefit psychologically to the pilot, since it opens up a much greater number of aerodromes which can be reached with a given payload. Thirdly, it provides considerable economy in operation by avoiding the necessity of station maintenance and operational

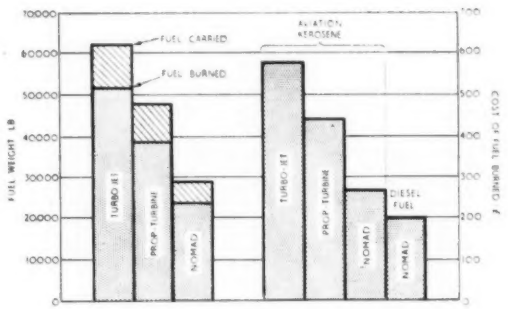


Fig. 7. Fuel requirements for London-Bahrein sector (3,150 *statute miles*)

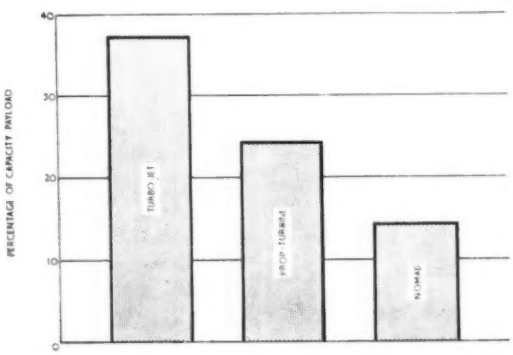


Fig. 6. Fuel reserves as a percentage of capacity payload

personnel, spare parts, and refuelling facilities, at intermediate landing points. Also, while the aircraft is on the ground there is the further chance of the weather deteriorating in such a manner as to prevent a take-off. Greater regularity will therefore be achieved if intermediate landing points are avoided. In addition, of course, the chances of a diversion somewhere along the route are increased in proportion to the number of intermediate landing points.

The cumulative effect of these factors is to neutralise the speed advantage which one aeroplane may have over its competitor if the latter has the longer range necessary to permit a particular sector to be flown non-stop. Fig. 8 gives an illustration of this for the London-New York sector. No jet-engined civil transport yet constructed is capable of flying this sector non-stop regularly during the winter months. In consequence, an intermediate stop is necessary. Gander, which lies on the direct route from London to New York, has been chosen as an intermediate stopping point, although it is equally likely that some other aerodrome, such as Goose or Montreal, which is not on the direct route, might have to be

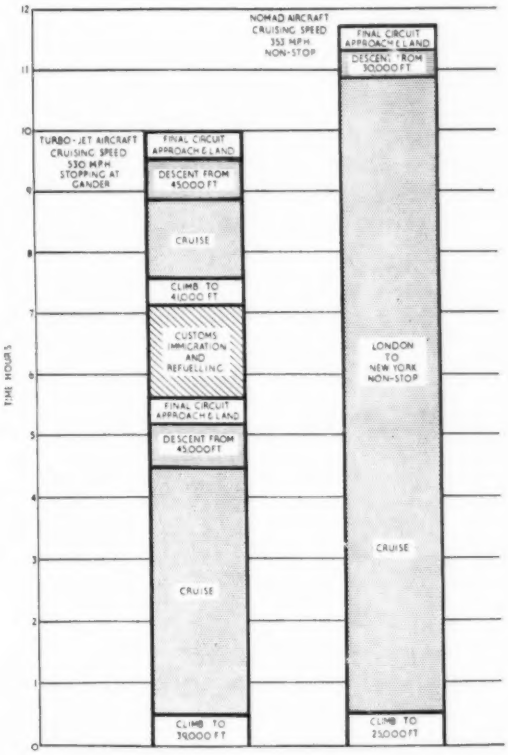


Fig. 8. Elapsed time London-New York for turbo-jet and Nomad engined aircraft

used. It will be seen that the pure jet aeroplane completes the journey from London to New York in 10 hours elapsed time, whereas the Nomad powered aeroplane, which can fly non-stop but whose cruising speed is 180 m.p.h. less, only takes 11·7 hours. Against this, the Nomad powered aeroplane would have the advantages in economy and regularity previously outlined.

The Landing Problem and its Effect on Safety and Regularity

In order to achieve its high cruising speed at altitude, the pure jet aeroplane must be exceptionally clean aerodynamically. As a result, in order to slow it down in the approach configuration, it is necessary to resort to a number of high-drag devices, and in order to bring it to a stop in an acceptable distance, special methods of retardation, such as tail parachutes, have to be employed. Even so, the landing distances required are very dependent on the accuracy of the pilot in maintaining the prescribed speeds. The landing distance regulations of the International Civil Aviation Organisation require the aeroplane weight and performance at landing to be such that it can be brought to rest within 60% of the available runway length. This is a severe requirement and is already proving critical for jet transports.

With a propeller, however, it is possible to reduce the landing run by means of reverse thrust, and the aerodynamic drag in the idling position also plays its part in reducing the landing run. Furthermore, because a propeller driven aeroplane will generally be lighter and smaller than the jet aeroplane carrying the same payload, the advantages of the propeller driven aeroplane in low approach speeds will permit reduced weather minima and, in

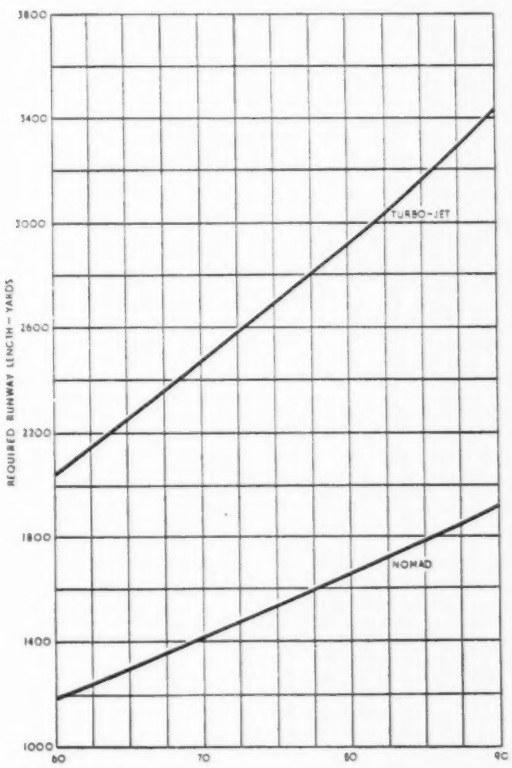


Fig. 9. Variation of landing distance with all-up weight (Distance from 50 feet to rest factored by 1·66)

consequence, regularity of operation will be increased.

Fig. 9 shows the required runway length for a given all-up weight (expressed as a percentage of the all-up weight) for the turbo-jet aircraft and the Nomad aircraft. The effect of braking propellers has not been taken into account for the Nomad aircraft, nor that of tail parachutes for the turbo-jet aircraft.

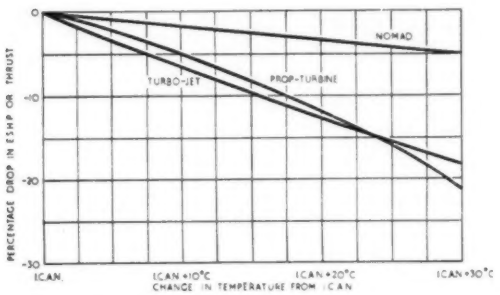


Fig. 10. *Temperature sensitivity*

Temperature Effects

The jet and the propeller turbine both suffer from significant deterioration in performance with increases in temperature. As a result, aircraft powered by such engines require long runways for take-off in high temperature areas. It is an unfortunate fact that it is often in such areas that, because of the low traffic density or the inadequate financial resources of the community concerned, the building of long runways is difficult to justify and, in consequence, operating weights must be reduced because of the runway lengths available. The Nomad, on the other hand, is much less sensitive to temperature effect.

As compared with its sea level I.C.A.N. performance* the Nomad loses only $2\frac{1}{2}\%$ of its equivalent horse-power for a temperature rise of 15°C, whilst both the turbo-jet and propeller

** The standard atmospheric conditions at sea level as defined by the International Commission on Air Navigation are 15°C temperature and 14.7 lb/sq. in. absolute pressure.*

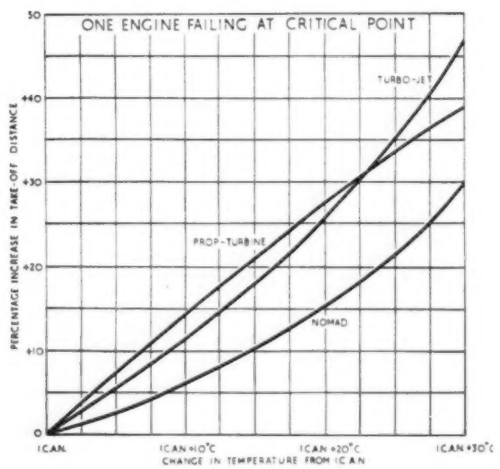


Fig. 11. *Variation of take-off distance with temperature*

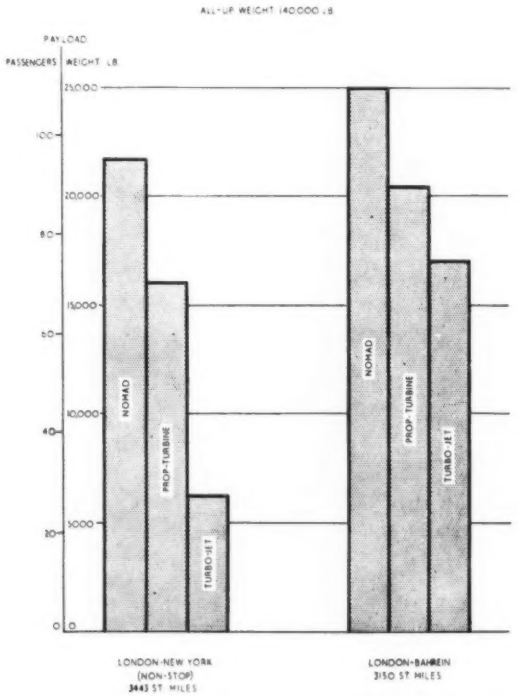


Fig. 12. *Aircraft of the same all-up weight and varying payload*

turbine lose approximately 9% under similar conditions. This is illustrated in Fig. 10, and Fig. 11 shows the variation in take-off distance due to changes in temperature for the three aircraft under consideration.

Flexibility

In order to achieve their optimum efficiency and most economical operation the jet and propeller turbine engines must be operated as high as possible. Their specific fuel consumption increases very rapidly as altitude is reduced, thus penalising aircraft with these types of power plants when it is not possible to operate at the optimum altitude, which is often the case in the event of bad weather, lack of navigational aids, or on short sectors.

The specific fuel consumptions, in lb/e.h.p.-hr at sea level static take-off power, of the three engines compared in this article are : Nomad ·36 ; propeller turbine ·624 ; and the turbo-jet 2·24. (The turbo-jet specific consumption has been related to equivalent horse-power in order to obtain a direct comparison with the Nomad and propeller turbine engines.) Like all other turbine engines, the specific fuel consumption of the Nomad improves with altitude and forward speed.

Varying Payload for same All-up Weight

The previous charts have shown comparisons of the results obtained from Nomad, propeller turbine and turbo-jet engines when installed in aircraft designed to carry 25,000 lb over a sector length of 2,860 statute miles. In order to achieve this carrying capacity the all-up weight of the three aircraft must reflect the fuel consumption of the three types of engine, with the result that whereas the Nomad version has an all-up weight of 123,000 lb the propeller turbine and turbo-jet versions have all-up weights of 140,000 and 153,000 lb respectively.

Fig. 12 shows the effect of using the same all-up weight (140,000 lb) for each aircraft. It will be seen that over the two sectors considered, the payload which can be carried varies very considerably with the type of power plant, and the low fuel consumption of the Nomad gives it a very significant advantage. The payload carried on the London-Bahrein sector can be compared with Fig. 5, in which different all-up weights have been assumed for the three types of aircraft.

The big difference in payload carried over the London-New York and London-Bahrein routes will be noticed from Fig. 12. This is because on the London-New York route the average effective route wind is a head wind of from 45 to 60 m.p.h., whereas on the London-Bahrein route the average effective route wind is a following wind of 20 m.p.h., these winds varying according to the altitude at which the aircraft is flying.

Water Turbine Governors

By N. G. DENNIS, M.A., D.I.C., A.M.I.C.E., A.M.I.Mech.E., A.M.I.E.E., Chief Engineer's Department.

PART II

Part I of this article was published in the June 1953 *issue of this journal, volume thirteen, number two, page* 82.

Special Functions of a Governor

A brief account follows of the special functions which a water-turbine governor may be called upon to fulfil.

Water Level Control.—Arrangements are sometimes made to control the head-water or tail-water level. In this event, the water level is relayed to the governor as a feed-back by some form of transmission. This transmission can involve a float and a mechanical linkage, a float and a geared-up synchronous electric transmission, or a pneumatic arrangement.

A transient feed-back to the governor from the water level in the surge tank or free-level canal is sometimes advantageous [7]. Such an arrangement can stabilise an otherwise unstable surge tank, but at the price of slow oscillations of the turbine power. This can be effected by a pressure-sensitive device at the turbine.

Frequency Control.—Three devices are available to check or actually control the frequency. These provide the value of frequency, the rate of change of frequency, and the difference between frequency time and accurate chronological time. This frequency control constitutes a slow secondary control of turbine speed. The control is usually manual, but can be automatic. It often operates the ' change of speed ' device of the turbine governor.

Sometimes a more rapid control than by the change-of-speed device is desirable. One proposal [8] has been to by-pass the governor actuator and to arrange that the frequency-sensitive device acts directly on the main servomotors. Water turbines are especially suitable for handling large sudden load changes since, unlike other turbines, the working fluid is always on tap and can be cut off quickly without thermal difficulty or waste.

Although ' tie-line bias ' control is recognised nowadays as the best method of controlling the power distribution and frequency on very large power systems, there are still instances where a selected power station is designed for sensitive isochronous governing. This plant then meets all the sudden changes of load on the network. The stable parallel operation of the generating units within this power station can be effected in several ways.

Tie-line Load Control.—Demand for close tie-line load control varies in different parts of the world according to national and power-company frontiers across which electrical energy is transferred.

Normally, a unit coupled to a network will have a ' speed-load ' droop which is produced by the rigid return motion in the main sequence from the servomotor movement. For tie-line control, this feed-back is removed and replaced by electrical measurement and transmission of the tie-line load. This unit is then responsible for the tie-line load and can cause a ' frequency-power ' characteristic between the interconnected networks. This is sometimes called ' tie-line bias ' control, and is very useful for the frequency and load control of interconnected electrical networks.

7 *M. Cuenod and A. Gardel* (1950). '*Stabilisation des oscillations des plan d'eau des chambres d' équilibre par asservissement temporaire de la puissance électrique à la pression hydraulique.*' *Bulletin Technique de la Suisse Romande, No.* 16. (*April* 1952), '*Étude des ondes de translation de faible amplitude dans le cas des canaux d'amenee des usines hydro-électriques.*'

8 *T. Stein* (1951). '*L'optimum nella regolazione delle turbine idrauliche.*' *L'Energia Elettrica, Vol.* 28 *No.* 4, *p.* 199.

An Actual Water-Turbine Governor

Water-turbine governors have been made for some years by The English Electric Company. Fig. 26 shows a section through, and some end views of, one model of actuator. The actuator is a major part of the low-power side of the control system, and is mounted on a servomotor. Fig. 27 shows the actuator mounted above a single, main servomotor in a non-enclosed arrangement. A diagram of this arrangement is given in Fig. 28, while Fig. 29 shows the centrifugal device and the combination element. Fig. 30 shows a block diagram for the actuator and servomotor.

The centrifugal device is of the type shown in Fig. 13. The governor has a temporary-return motion which is shown in Fig. 18a, and its location is shown in the bottom right-hand corner of Fig. 26. The permanent-return motion is produced by the vertical movement of the spindle mounted behind the front cover of the actuator, and this has a cam with an inclined face mounted on it which bears against a roller that can move horizontally.

The combination element in this case combines the speed deviation, the temporary-return motion,

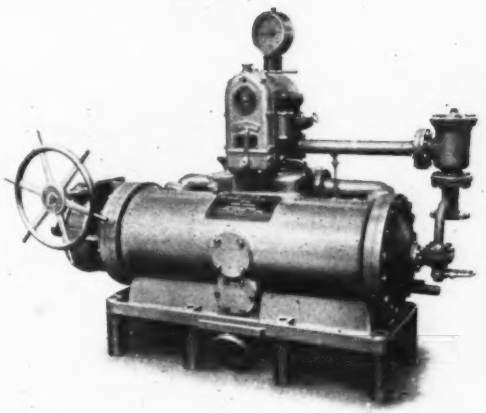


Fig. 27. Governor actuator and servomotor

the permanent-return motion, and the change-of-speed movement. It consists mainly of a special quadrant which is shown in Figs. 26 and 28. This quadrant combines all the quantities just mentioned, with the exception of the change-of-speed movement which is added later in the sequence. The

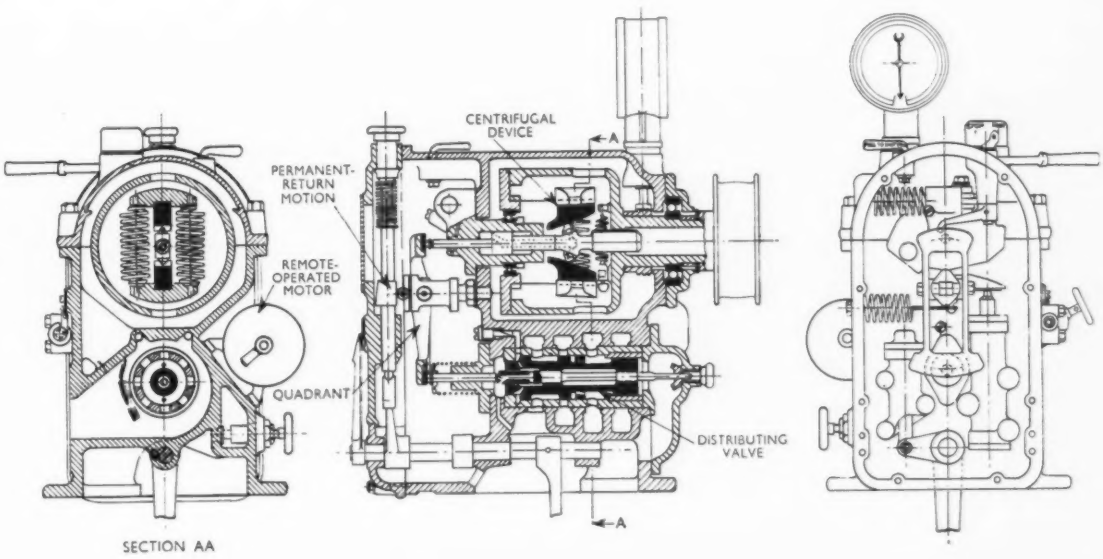


Fig. 26. Automatic governor actuator

quadrant is a floating lever (Fig. 14) which has an extra degree of freedom caused by a transverse swivelling action. The ends of the quadrant have inclined faces so that the transverse rotation produces relative movement between spindles bearing against the faces. The summated movement from the quadrant operates the distributing valve through a pilot nozzle of the type shown in Fig. 15a. The change-of-speed movement is introduced by variation of the position of the nozzle relative to the piston of the distributing valve. This is done by mounting the nozzle at the end of a spindle which is screwed into the piston of the distributing valve. A motor, remotely operated, controls the setting of the change-of-speed device. Rotation of this motor causes the spindle in the distributing-valve body to rotate to a new position, the effect of which is to add the change-of-speed movement to those quantities already combined in the quadrant. In effect, the change-of-speed action is produced by varying the length of the spindle between the quadrant and the distributing valve. The temporary-return motion is that shown in Fig. 18a. The distributing valve and servomotor are arranged to integrate as in Fig. 6a.

Since hydro-electric stations are often situated in remote places, it is essential that a water-turbine governor is designed for the utmost simplicity and reliability. Construction must be sturdy and all sensitive devices must be properly enclosed and protected, and yet easily accessible. Maintenance must be made as easy as possible. At the same time, sensitivity and rapidity of action of the governor must amply satisfy requirements of the electrical network.

All working parts of the governor are automatically lubricated to ensure minimum wear and maximum life. Oil strainers guard against the entry of foreign matter. The servomotors can be hand-operated in case of emergency. Different arrangements of servomotors are used for different conditions.

It is essential that all such governors should be thoroughly tested at the factory before despatch. The final setting of the various adjustments on a governor can be done only under site conditions, and easy adjustment is provided.

The actuator is designed for different sizes of turbine and different types of control and protective systems. Control schemes have been extended to complete automatic control with remote supervisory operation, which includes the starting and stopping of the turbine. These control schemes require the utmost co-operation between all the engineers concerned.

Stability of Regulation

The construction of water-turbine governors is very closely linked to the choice of the necessary moment of inertia of the rotating parts (GD^2) of the generating set. Present-day practice in the choice of GD^2 is largely based on semi-empirical figures of the overspeeds and the over-pressures which follow major load rejections. In the view of many authorities on the subject, guarantees should be transferred to the more logical bases of margin of stability and closeness of speed control. The old theory is regarded by many as an obstacle in the path of technical progress towards cheaper and lighter generating sets.

With certain important types of plant, the basic hydro-mechanical difficulties of governing are increasing. In other words, the hydraulic inertia is tending to increase and the mechanical inertia of rotation is tending to decrease. Big low-head Kaplan turbines for run-of-river stations and tidal power plants are encountering hydraulic time constants up to 4 sec., compared with the more usual figures of 1-1.5 sec. A further difficulty of governing is the development of higher specific speeds for such plants, since this means a flatter torque-speed curve of the turbine, hence poorer self-regulation. Also some recent very high-head Pelton plants have large hydraulic time constants on account of high water velocities in the penstock.

In addition, an effort is being made to cheapen the main generators by reducing the weight. This entails a reduction in the 'natural GD^2' of the generator. However, on the old theory, higher overspeeds are likely to become permissible because of a more accurate theoretical approach, better experimental data, and less fundamental mechanical and electrical concern over the value of the overspeed attained, providing that this is well within the runaway speed and stability is not endangered.

In connection with power-system control, Crary[9] comments that the first stage of development is just finishing, and the objective of this stage was no more than to furnish a sufficient amount of reliable power to the consumer. It is considered that a second stage is just beginning, where greater consideration must be given to capital investment and operating cost in order to obtain greater overall economy.

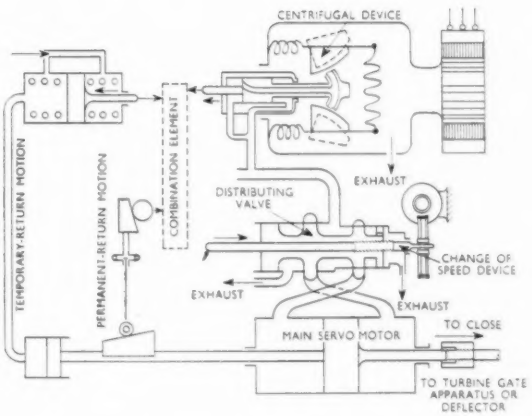


Fig. 28. Diagram of water-turbine governor

Water-turbine governors are often applied to tie-line bias control of the connections between electrical networks. The governor then usually responds to net-interchange variations, and in this case it attempts to keep the total power exchange constant on all tie-lines radiating from the system. By such automatic control, interconnections are operated nearer stability limits, tedious manual control is eliminated, and mutual co-operation between adjacent networks is greatly improved. A special case of tie-line load control is that where the effect of very heavy fluctuating loads such as steel mills can be localised. These big load changes can be met locally by providing an adjacent power station with rapid-action governors. These severe power variations, then, do not affect the bulk of the network and do not upset the normal steady distribution of electricity ; in this way the danger of losing synchronism with the rest of the network also is reduced. On any network, the rates of response of the various governors have to be matched adequately to give stability of the team response to load changes ; otherwise, a small system when violently disturbed may drop out of step.

The tendencies in the design of water-turbine governors probably are two-fold. For very large stations, the expanded requirements of the network tend to require a greater degree of complexity. On the other hand, small generating sets will be more and more regarded as inseparable members of a team where individual regulation guarantees may be greatly relaxed. For many such turbines the centrifugal device probably will be omitted from the governor. One advantage of such an arrangement is the alleviation of the high relative cost of the governors for small stations ; and, also, the surge tank frequently can be reduced in size or avoided.

The foregoing paragraphs have dealt briefly with the relationship between the water-turbine governor and the electric network. In recent years, the importance of the governor in the other direction of the overall control pattern has been more appreciated. Evangelisti [10] and Stein [8] have pointed out that the stability constants of the governor and the self-regulation of the turbine and its connected load have quite an appreciable effect on the stability of surge tanks. The stabilising effect of the governor on the surge tank can be further improved by a transient feed-back from the surge-tank water level to the turbine governor.

Surge-tank stability may be influenced by interconnection of hydro-electric plants which have surge tanks of very different time constants ; such interconnections increase the stability of the individual surge tanks. However, it is recognised that interconnection of generating sets does not in itself produce any appreciable increase of governor stability ; a hydro-plant which is individually unstable can work satisfactorily when connected to the network, but only at the price of a decrease in the margin of stability in the whole network. In fact, water-turbine governors frequently incorporate a device which, by reducing the stabilising action of the governor, increases the rate of action when

9 *S. B. Crary* (1947). ' *Power system stability* ' (*John Wiley, New York*).

10 *G. Evangelisti* (1950). ' *Pozzi piezometrici e stabita di regolazione* .' *L'Energia Elettrica Nos. 5 and 6.*

required for rapid frequency control on a large network.

It is seen that features which were previously considered to be independent control problems, such as the surge tank, the governor, and network control, are now being increasingly regarded as one comprehensive control scheme. Such an approach promises increased overall economy of construction, since severe problems encountered in one quarter frequently can be overcome by appropriate action in another quarter. Thus, for example, an awkward question of governor stability may be relieved greatly by suitable design of the automatic voltage regulator so as to improve the self-regulation characteristic of the generating set.

There is still a great deal of work to be done towards improving practical knowledge of this very intricate question. It is likely that greater recourse will be had to model experiments and simulators. Probably, such experiments will co-ordinate present-day processes for the investigation of individual problems such as surge-tank and free-level channel stability by hydraulic models, of governor behaviour by hydraulic models or servo-simulators, and of network behaviour by network analysers.

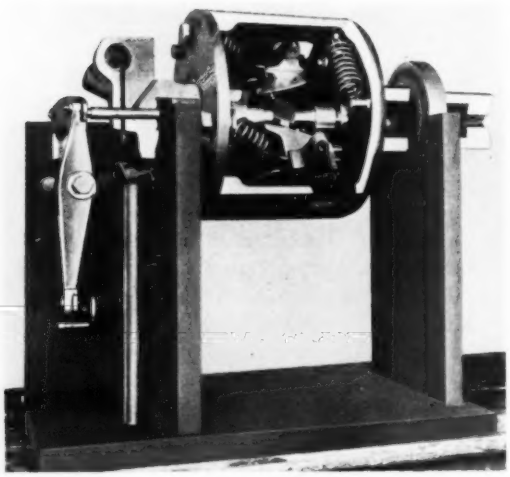


Fig. 29. Cut-away centrifugal device and combination element

Simple Governor Theory

Although the following theory embraces the main influences on water turbine regulation, there are many other factors which may affect the results obtained. This theory applies specifically to the temporary-return-motion governor, but the theory for acceleration-sensitive governors is very similar and leads to the same general condition of stability.

The assumptions made in this simple theory are :—

(1) The generator supplies a purely resistive load under the influence of an infinitely rapid voltage regulator, so that the electrical power which resists the rotation of the main shaft remains constant during transients. In practice, this assumption is unfavourable to the governor since it means that the resisting torque will decrease as the speed increases. Hence, the speed increase will be exaggerated and stability worsened.

(2) Constant efficiency of the turbine over its range of transient operation.

(3) Travelling pressure waves, due to water hammer in the hydraulic system, are ignored and the water is considered as a concentrated mass.

(4) Negligible time delays in the centrifugal device and in the relays of the governor.

Notation

K_0 A constant, defining the rate of action of the distributing-valve and servomotor.

T_r Time constant of dashpot.

y_0 Steady-state opening of the guide vanes.

ε Relative increment of guide-vane opening.

ζ Relative increase in head due to water-hammer.

η Effect of temporary-return motion as described by a relative speed increment (hypothetical) which would affect the distributing valve by the same amount.

θ Time constant of the hydraulic conduit (ratio of the momentum of the water to the product of the head and the acceleration due to gravity).

ξ Relative speed increment (ratio of actual increment of speed to steady-state speed).

σ Stroke of temporary feed-back (measured as though the dashpot were rigid).

τ Time constant of rotation of runner-rotor (ratio of kinetic energy at normal speed to steady-state power).

τ' A characteristic time, describing the slowness of regulation of the whole governor.

Equation of Centrifugal Device, Distributing-valve, Servomotor and Return Motion.

$$\frac{d\varepsilon}{dt} = -K_0(\xi + \eta), \quad \ldots\ldots (1)$$

where $\xi+\eta$ describes the displacement of the distributing-valve due to the sum of the displacements of the centrifugal device and the return motion. The rate of movement of the servomotor is proportional to this. The effect of an acceleration-sensitive device can be added if desired.

Equation of Dashpot in the Temporary-return Motion.

$$\frac{d\eta}{dt} = \sigma\frac{d\varepsilon}{dt} - \frac{1}{T_r}\eta \quad \ldots\ldots (2)$$

With reference to Fig. 18b, this equation equates the velocity of the output to the velocity of the input minus the relative velocity of the piston within the dashpot.

Equation of Rotation of Runner and Rotor.

$$\tau\frac{d\xi}{dt} = \varepsilon + \frac{3}{2}y_0\zeta \quad \ldots\ldots (3)$$

Acceleration is the effect of increased driving torque due to the change in the guide-vane opening and the increase in water pressure due to bulk water-hammer. This stabilising effect of self-regulation can be introduced into this equation if desired.

Equation of Bulk Water-hammer.

$$\zeta = -\theta\left(\frac{d\varepsilon}{dt} + \frac{1}{2y_0}\frac{d\zeta}{dt}\right) \quad \ldots (4)$$

The pressure rise is proportional to the deceleration of the water in the pipe-line. This deceleration is the combined effect of the rate of closure of the guide vanes and the rate of increase of pressure. The effect is to produce instability.

Overall Response Equation.—The overall response equation, as derived from the above four equations, is

$$\frac{\tau\theta y_0}{2}\cdot\xi^4 + \tau\left(1 + \frac{y_0\theta K_0\sigma}{2} + \frac{y_0\theta}{2T_r}\right)\xi^3 + \left\{K_0(\tau\sigma - y_0\theta) + \frac{\tau}{T_r}\right\}\xi^2 + K_0\left(1 - \frac{y_0\theta}{T_r}\right)\xi + \frac{K_0}{T_r} = 0 \quad (5)$$

The distributing valve and servomotor can usually be assumed to act very quickly and hence K_0 can be assumed infinite.

This reduces the equation to

$$\frac{\tau\theta\sigma}{2}\xi^3 + (\tau\sigma - \theta)\xi^2 + \left(1 - \frac{\theta}{T_r}\right)\xi + \frac{1}{T_r} = 0, \quad (6)$$

when the turbine is operating at the most unstable condition, which is usually at full load ($y_0 = 1$). When the Routh stability criteria are applied to the coefficients of equation (6), the following two conditions result :—

Condition (1)

$$\sigma > \frac{\theta}{\tau}$$

This is identical with the condition mentioned by Thoma (1924) for permanent-return-motion governors. It specifies the minimum stroke of the temporary-return motion.

Condition (2) (Almeras[11] and Gaden[12])

$$\frac{(\sigma T_r)\tau}{\theta^2} > 3{\cdot}74$$

Now the slowness of regulation of the whole governor is controlled by the temporary-return motion, that is σ and T_r and, in fact,

$$\tau' = \sigma T_r$$

Therefore, $\tau'\tau > 3{\cdot}74\theta^2$.

Thus the product of the slowness of regulation (a time τ') and the time constant τ of the runner-rotor, cannot have a value less than the value determined by the hydraulic conditions.

Further Considerations

There are many factors which also affect the stability of governing of the individual generating set. Stability is improved if :—

(1) The efficiency increases as the gate opening increases. This provides for alteration in the turbine power with a smaller change of flow through the turbine. Hence, one unstabilising influence—that of water hammer—is reduced.

(2) The consumer's load embodies appreciable inertia. Such inertia is, of course, coupled electrically to the flywheel effect of the generating set. Although this electrical coupling is not absolutely

11 *P. Almeras* (1946). '*Influence de l'inertie de l'eau sur la stabilité d'un groupe hydro-électrique.*' *La Houille Blanche*, No. 3.
12 *D. Gaden* (1945). '*Considérations sur la problème de la stabilité*' (*Editions La Concorde, Lausanne*).

rigid, it has a very beneficial effect on stability. Evidently, any increase in the moment of inertia will improve regulation, since the stored energy in the system is then increased and is available to aid the governor action during load changes.

(3) There is favourable difference between the power-frequency characteristics of the generating set and of the load. This property is called ' self regulation,' which can be described most conveniently by considering the steady driving torque of the turbine relative to the steady resistance torque provided by the electrical load. The turbine driving torque will always decrease with an increase in speed, whereas the resisting torque will usually increase. The difference tends to slow down the generating set, and constitutes a corrective and stabilising influence.

In general, the magnitude of the electrical load is dependent on the voltage as well as on the frequency supplied by the generating set. Since any voltage regulator gives a transient voltage rise when the speed increases, a further increase in the resistance torque results, with consequent improvement of stability. The effect occurs to some extent with any voltage regulator but is more pronounced with older designs. The latest automatic voltage regulators tend to be very rapid in action and should be considered carefully in this connection, since they reduce the ' artificial ' self-regulation due to transient voltage change.

Statistical analysis has been employed to ascertain the total self-regulation effect of the miscellany of loads connected to a power system.

Sometimes governor tests are made during the commissioning by means of water resistance load on the generating set. It should be recognised that such conditions will usually constitute an abnormally severe self-regulation effect and that the turbine governor should not be adjusted finally during such tests.

A further influence on stability is the travelling wave of water hammer in the pipelines of high-head plants[13] [12]. Such water-hammer waves, of course, occur in the supply and discharge conduits of every plant. However, with low- and medium-head plants, the wave action is negligible and the effect is as though the water were concentrated in a single mass. With high-head plants it is important that the governor does not resonate with the water hammer.

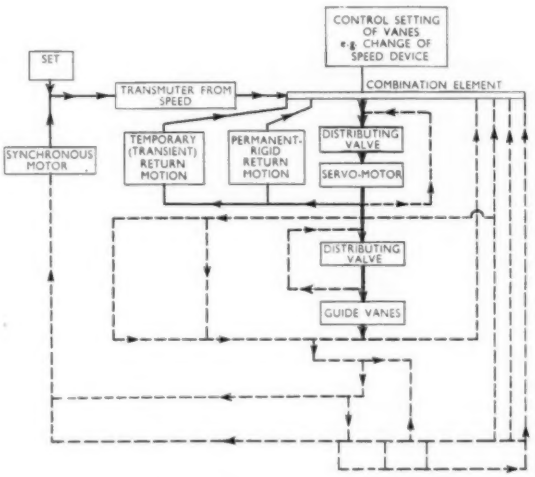


Fig. 30. *Diagram of governor action*

These influences can be taken into consideration by modifying the formula $\tau'\tau > 3.74\theta^2$ into $\tau'\tau > k\theta^2$ where k is a function of the influences described.

It should be mentioned that double regulation cannot be regarded as affecting the stability of small oscillations. It affects only the amplitude of large oscillations, since the deflector, diffuser and relief valve bring about a transient flow diversion only for big load rejections and not for increases, nor for very small decreases, of load. This transient flow diversion could be arranged to improve stability, but only at the price of a continual waste of water. The runner blades of a Kaplan turbine usually move slowly in relation to the guide-vanes and thus do not influence stability to any great extent.

On some large power systems, many generating sets are operated at a fixed gate opening, i.e. the opening is not decided by the frequency but by the river flow with a run-of-river plant, or by the water level in the case of a power station having large reservoir capacity. Such plants can be considered to have an infinite slowness of regulation

13 *See D. Gaden and P. Neeser* (1948). *' Influence des certaines caractéristiques intervenant dans la condition de stabilité.'* (*Editions La Concorde, Lausanne.*)

and, from Condition (2) of the Simple Governor Theory, it will be seen that this means ample stability. However, frequency regulation would be bad but for the facts that special frequency control plants are provided, and that the electrical networks are extremely large. It can be shown statistically that the frequency deviations due to load changes on the network are roughly proportional to the square root of the total power capacity of the network. Obviously, a sudden 10 MW load change will produce a greater frequency deviation on a small network than on a large one.

The quality of frequency regulation also is roughly proportional to the rapidity of action of the governors controlling the frequency ; and the error in frequency varies as the slowness of the governor regulation. It may be noted here that, with any servo-system, there is a certain conflict between the attainment of stability and the attainment of accuracy of control. Accurate control demands a high rate of action of the controlling mechanism and this is limited by the incidence of instability.

A further brief reference to the electrical stability of power systems is necessary. Space here does not allow a detailed consideration of this subject which is, however, extremely important and complex. In general it concerns the pole-swinging of the synchronous generators and motors connected to the power systems, particularly after severe electrical faults which, of course, constitute a sudden shock loading of the system. It is usual practice to ignore the influence of the rapidity of action of the governor on the transient stability. The reason for this is that governors are relatively slow in action compared with the time constants which control these power system oscillations. Nevertheless, an improvement in the rapidity of action in the governor does have a slight improvement on the transient stability because, within the practical limits possible, the turbine output is more rapidly reduced subsequent to a severe drop in generator load due to a fault. If possible the time lag of the governor and its natural frequency of oscillation should not approach the natural period of the electrical system, since this can bring about resonant oscillations. On the other hand, governors have an important effect on the steady-state stability since they control the division of the load changes amongst the various generating units and hence the behaviour when the limit of static stability is approached.

Likewise the rate of action of the generator excitation system as a whole and the voltage regulator have no great effect on transient stability, but are important in connection with steady-state stability. A fast rate of action enables operation to be nearer the steady-state stability limit, since a smaller margin can be allocated to deal with normal perturbations occurring in the system. There is thus a certain amount of conflict concerning the desirable rate of action of the voltage regulator since an increase in its rate of action, although improving system stability, has a detrimental effect on the self regulation discussed previously.

As regards the earlier basis for determining the requisite moment of inertia, Almeras has shown that these prescribed conditions have a certain logical basis. He has shown that the stability and the quality of regulation correspond roughly to the product of the rise in pressure and the rise in speed, on sudden rejections of load. Thus, in the modern view, importance is not placed so much on the over-pressure or the over-speed *per se* but rather on the product of these two. While the values of over-pressure and over-speed concerned are those obtaining without relief valve, deflector or diffuser, this is not always the case in the practical application of the earlier basis which contributes further to a lack of theoretical integrity.

Insulation Co-Ordination in High-Voltage Stations

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INSULATION CO-ORDINATION is the correlation of the insulation strengths of the various parts of an electrical system to minimise damage due to overvoltages and to localise unavoidable flashovers.

In a switching station this requirement is met if all the items of equipment, such as circuit-breakers, transformers, post and tension insulators, have ' withstand ' voltage characteristics greater than the protective level of the surge diverters or the air gaps provided for overvoltage protection.

The level of insulation selected for the transmission lines, which represent by far the greater part of any network, depends on their location, exposure to lightning and liability to contamination ; it is not necessarily directly related to the switching station insulation level.

As lightning is the major hazard to electrical equipment, co-ordination of insulation is applied principally to outdoor high-voltage systems.

Overvoltages

There are two types of overvoltages which may arise in a system:—

(*a*) System frequency;

(*b*) Transient.

The latter may be internally generated (switching overvoltages) or of external origin (lightning).

SYSTEM-FREQUENCY OVERVOLTAGES

These may occur under fault conditions and their magnitude depends on the nature of the fault and the method of system earthing. The maximum R.M.S. line/earth voltage can be calculated by the use of symmetrical components from the constants of the system, the type of fault and the fault impedance. On an effectively earthed system with a single line to earth fault the maximum R.M.S. voltage to earth on any phase will not exceed 80% of the normal line/line R.M.S. voltage, but if the system is earthed through an impedance the maximum line/earth voltage can, in some circumstances, exceed the normal line/line voltage.

On an insulated neutral system high overvoltages are possible where the zero sequence reactance is capacitive and the resistive components of the network are small. For this reason operation of high-voltage systems with unearthed neutrals is not generally recommended.

Further causes of power-frequency overvoltage are over-speeding of hydro-electric plant following loss of electrical load, and voltage rise on long unloaded transmission lines.

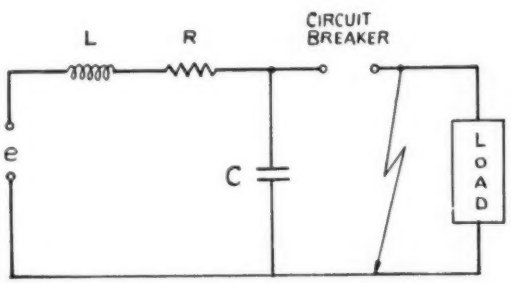


Fig. 1. *Generation of a switching surge*

Normal system-frequency overvoltages which persist only for a short time, usually not more than a few seconds, are termed ' dynamic overvoltages.' Those which persist for long periods are termed ' stationary overvoltages '.

TRANSIENT OVERVOLTAGES

Internally Generated Overvoltages

When a sudden change is made in an electrical

system a transient voltage is produced. The elementary circuit shown in Fig. 1 represents one phase of a three-phase power system in which ' e ' is the phase/neutral voltage of a generator, L and R the inductance and resistance of the system on the supply side of the circuit-breaker, including that of the generator, and C the capacitance to earth.

Assume that the circuit-breaker is closed and that an earth fault occurs close to it which effectively short-circuits the capacitance C. If then the resistance R is small compared with the reactance L, the current will lag the voltage by approximately 90 electrical degrees ; that is, at current zero the voltage will be at its crest value. If, however, the fault is cleared at a current zero, the voltage at the supply terminals of the circuit-breaker will not be restored instantaneously since the capacitance has to be recharged and when normal voltage is reached the energy stored in the inductance during this charging period is discharged into the capacitance to cause overshooting of the voltage. The peak voltage reached and the nature of the transient is dependent on the system constants ; the voltage wave will generally be oscillatory. With no resistance in the circuit the maximum peak of the restriking voltage would be twice the crest value of the normal system phase/neutral voltage.

This explanation is considerably simplified by the assumption that a system can be reduced to a simple oscillatory circuit ; in practice the various parts of a large system may oscillate independently thus producing a complex oscillatory wave containing components of two or more frequencies.

Transients can also occur when switching unloaded lines or capacitors. When the circuit is interrupted at current zero the supply voltage is at its maximum and there is no voltage across the circuit-breaker. As the line or capacitor retains its charge for a time, the voltage which appears across the circuit-breaker a half-cycle later will be twice the normal crest value and, if the arc restrikes, a transient oscillation will occur which can result in a maximum voltage to earth of three times the crest value of the normal phase/neutral voltage. Higher voltages are theoretically possible should the arc again be interrupted and restrike at appropriate half-cycles.

In a similar manner arcing faults on an insulated neutral system can give rise to the build-up of dangerous overvoltages which cannot be controlled by circuit-breaker design.

In the examples given, interruption has been assumed to take place at current zero. When switching small currents, as, for example, a transformer on no-load, the current may be interrupted before it reaches the normal zero and such ' current chopping ' can give rise to transient overvoltages.

While records of switching surges on systems of different voltages, and transient analyser studies, have shown overvoltages to earth as high as five times normal line/neutral crest voltage, switching surges on earthed neutral systems rarely exceed three times normal line/neutral crest voltage.

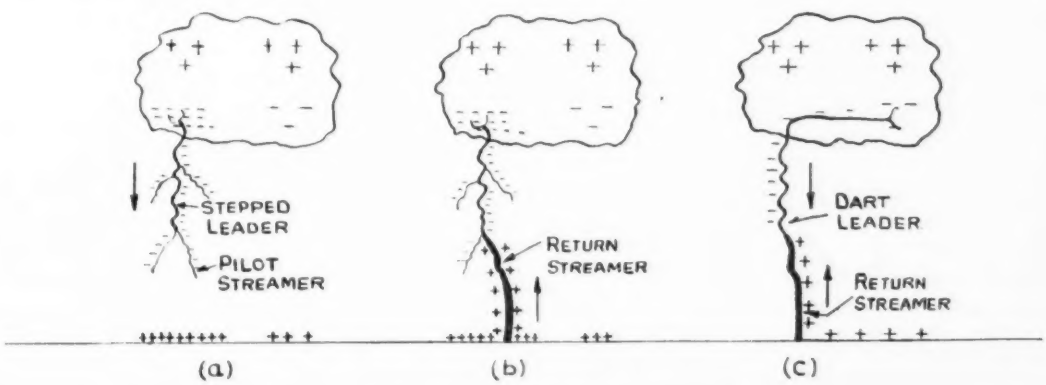


Fig. 2. Formation of a lightning stroke

Lightning Overvoltages

A thunderstorm occurs when a cloud becomes charged to a voltage which is so high that the surrounding air can no longer completely insulate the cloud from earth. When this happens a small corona discharge called the ' pilot streamer ' moves a charge from the cloud into space towards the earth. This pilot streamer ionises the air and provides a path for a current arc, the ' stepped leader,' which is the first visible part of the lightning stroke (Fig. 2a). The stepped leader gets its name from the way in which it travels in steps, about 150 feet long, arranged in zig-zag formation. The stepped leader, with outbranching streamers, continues on its way and when it reaches earth a charge of opposite polarity immediately travels from earth to the cloud along the ionised path formed by the leader (Fig. 2b). It is this ' return streamer ', the current of which flows in the same direction as the current in the leader, which causes the well-known flash of lightning.

When this chain of events has passed, the portion of the cloud near the point where the pilot streamer originated has been discharged, but other parts of the cloud may retain their charge. They may then discharge to earth in the form of a non-branching ' dart leader ' along the ionised path provided by the first stroke, and so cause another high-current return streamer to move to the cloud (Fig. 2c). This process may be repeated a number of times to give a multiple or repetitive stroke. Most strokes have at least two separate discharges and as many as forty discharges have been recorded in a single stroke ; the time between components may vary from one-half to one-thousandth of a second.

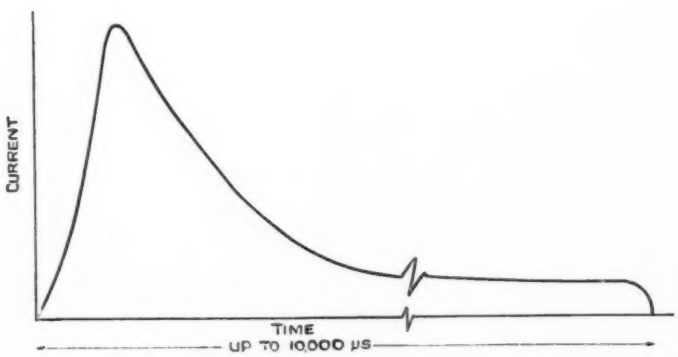


Fig. 3. Stroke of ' hot ' lightning

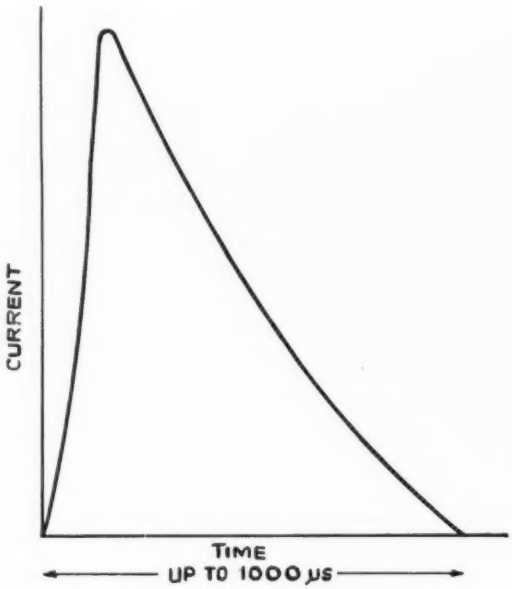


Fig. 4. Stroke of ' cold ' lightning

In this description discharges from cloud to earth only have been considered since it is these discharges that concern the electrical engineer ; strokes may occur in a similar manner between clouds. Of strokes to earth, about 90% are negative strokes (*i.e.* the cloud has negative and the earth positive polarity) although positive strokes can also occur. All lightning strokes are unidirectional.

The magnitude of the current in a lightning stroke, and its duration, can vary within wide limits. Figs. 3 and 4 show typical discharges. Fig. 3 shows a stroke consisting of two parts, a high current short-time initial component and a low current long-duration tail. This is typical of a stroke of ' hot lightning ' which is the kind of stroke which tends to cause fires when it strikes a tree or house. Fig. 4 shows a typical stroke of

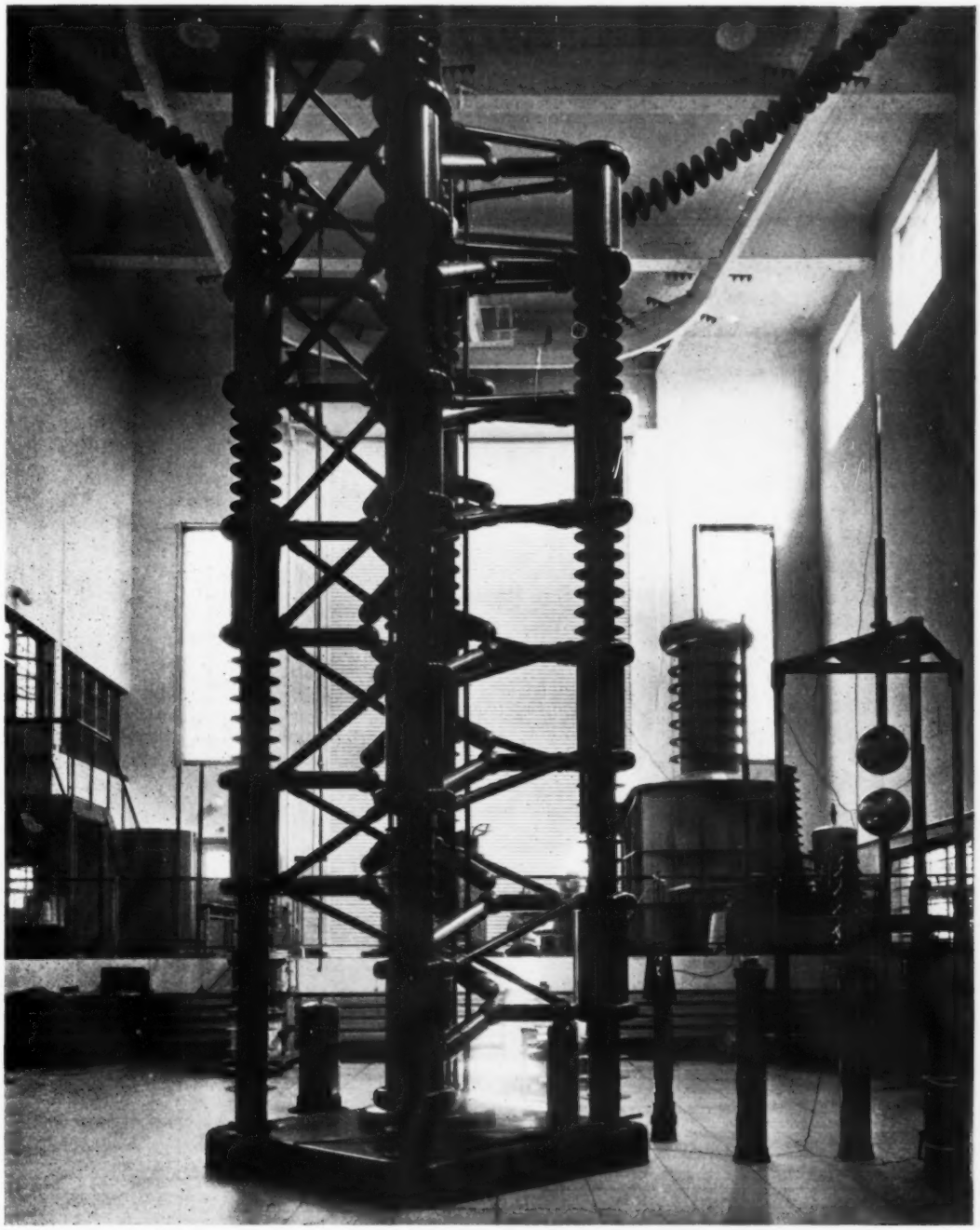


Fig. 5. Impulse generator in the Nelson Research Laboratories at Stafford

'cold lightning' which is the kind of discharge which causes explosions, rather than fires, when it strikes a structure ; it is of much shorter duration than the 'hot lightning' discharge.

It is often of interest to the system design engineer to know whether the area in which equipment is to be installed is one where 'severe' lightning conditions are to be anticipated. Data on the frequency of lightning is somewhat difficult to obtain and, in general, the only information available comes from the local meteorological service which will usually record the number of

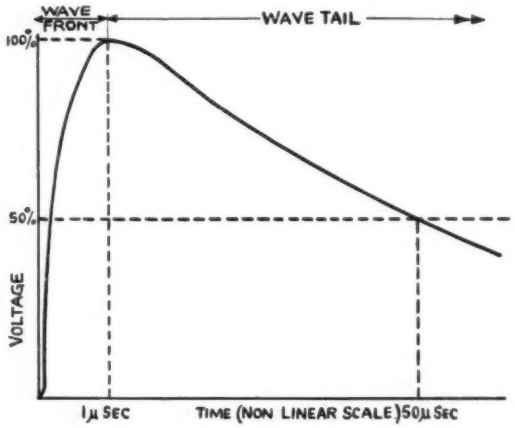


Fig. 6. 1/50 *microsecond impulse*

days in the year on which thunder is heard. This number is commonly referred to as the 'isoceraunic level' and it provides a very rough-and-ready indication of lightning severity ; it is somewhat unsatisfactory in that it gives no information on the number of individual strokes occurring during the days when thunder is heard. The isoceraunic level in Britain is about 15, whereas values exceeding 100 are encountered in some tropical areas.

Impulse Testing and Insulation Levels

Until comparatively recent years the design of equipment and installations subject to lightning had to be based on performance under power-frequency (normally 50 cycle) high voltage tests, although in fact system-frequency overvoltages of the magnitude used for testing could not possibly occur in service. The knowledge gained of the

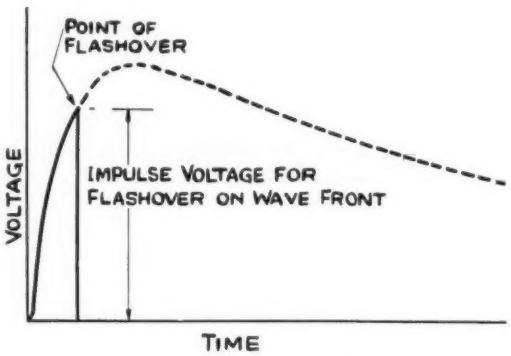


Fig. 7. *Flashover on wave-front*

nature and behaviour of lightning, however, has led to the introduction of impulse voltage testing of high-voltage equipment and to insulation co-ordination being based primarily on impulse performance. The impulse generator used by The English Electric Company is shown in Fig. 5 and is capable of producing 3,200 kV.

As previously mentioned, the magnitude and wave shape of lightning strokes vary greatly and it has therefore been necessary to lay down standards of wave shape for impulse testing. An impulse is an artificially produced unidirectional transient of controlled wave shape and amplitude, and the British standard impulse voltage wave has a front of 1 microsecond and a time to half-value of wave tail of 50 microseconds, as shown in Fig. 6. This is normally referred to as a 1/50 full wave and its voltage is specified by the maximum amplitude, or peak value. The impulse may be either of positive or negative polarity. The American standard is a

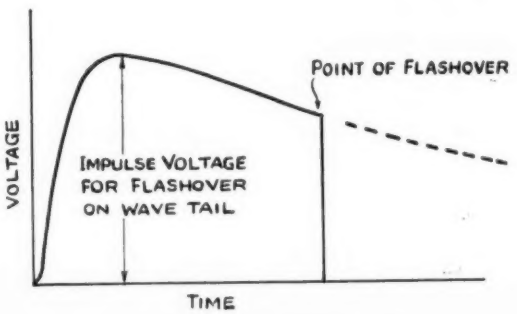


Fig. 8. *Flashover on wave-tail*

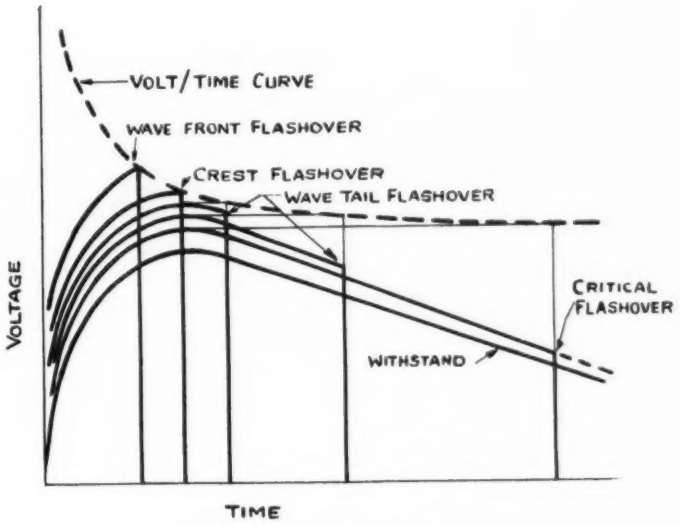


Fig. 9. Formation of volt/time curve

$1\frac{1}{2}/40$ wave, but in most practical cases test results are very little affected by the slight differences between the two standard shapes. The tolerances on the time to crest and to half value permitted by British Standard 923 : 1940 (' Impulse Voltage Testing ') are such that a $1\frac{1}{2}/40$ wave just lies within the B.S. tolerance limits of a 1/50 wave.

For most apparatus it is necessary to know the ' impulse withstand ' value, since this is the maximum voltage at which breakdown of insulation does not occur under impulse test, but for some apparatus the ' 50% impulse flashover voltage ' is mentioned and this is defined as the peak value of the impulse voltage which causes flashover of the object under test for about half the number of applied impulses.

When the object under test, or the test gap, flashes over it ' chops ' the impulse wave ; this chopping may be on the wave front as shown in Fig. 7 or on the tail as in Fig. 8. For flashovers on the wave front the flashover voltage is defined as the voltage at the point of flashover. For wave tail flashovers the flashover voltage is the peak value of the impulse wave causing flashover.

The impulse ratio of an object is the ratio of impulse flashover voltage to the peak value of the power-frequency flashover voltage, and the value normally quoted is the ratio obtained by using the 50% impulse flashover voltage. For a sphere gap the impulse ratio is 1.00 but for the great majority of other gap configurations the impulse ratio is greater than unity.

Standard impulse voltage levels have been laid down in British Standard 116 : 1952 for outdoor type oil circuit-breakers. These are ' withstand ' values, and are given in the following table :—

Table I

Rated Service Voltage	Impulse Withstand Test Voltage	
	Non-effectively earthed systems	Effectively earthed systems
kV	kV	kV
22	150	150
33	190	190
44	260	260
66	330	330

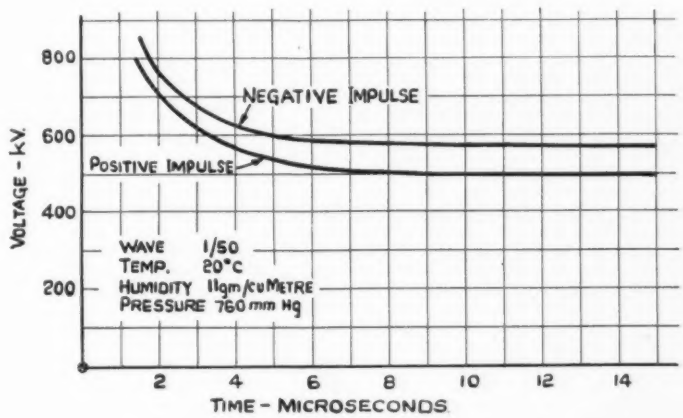


Fig. 10. Impulse breakdown characteristics of 30-inch rod gap

88	450	450
110	550	450
132	630	550
165	730	630
220	1,050	890
275	—	1,050

These impulse insulation levels are generally applicable to transformers as well as switchgear. They compare closely with American standard basic insulation levels (BILs) and those determined by practical experience of protection levels afforded by surge diverters.

Impulse Characteristics of Equipment

The equipment in an outdoor substation consists of busbars and connections with support and suspension insulators, isolating switches, circuit-breakers and in most cases transformers. Over-voltage protection may be provided by simple rod gaps, expulsion gaps, or surge diverters, and may include earth wires.

The impulse characteristics of the various items of equipment differ, but in all cases flashover, or breakdown voltage, varies with the duration of the applied impulse.

AIR GAPS

Air gaps in a station take the form of rod gaps (or rings) used as arcing horns on insulators and bushings, or separate co-ordinating rod gaps mounted on or near transformers.

If an impulse voltage slightly in excess of the maximum withstand value is applied to an air gap, sparkover will occur on the wave tail. With increasing voltage, sparkover will occur correspondingly earlier until the crest flashover value is reached (*i.e.* sparkover takes place on the crest of the impulse wave), and if the voltage is still further increased sparkover will occur on the wave front.

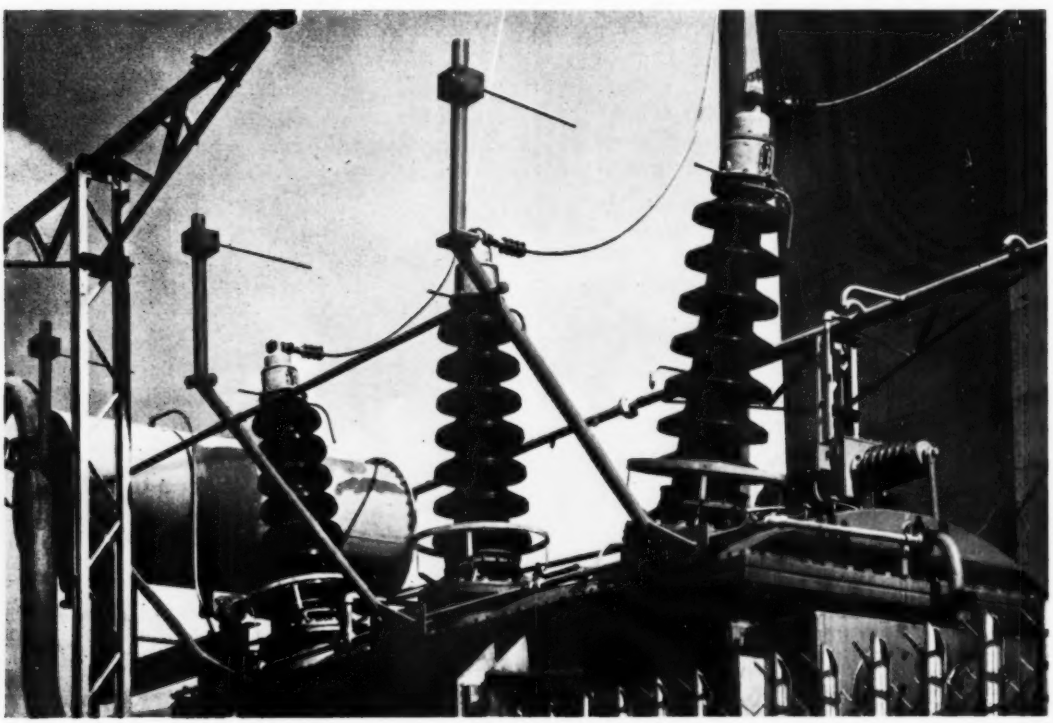


Fig. 11. *Co-ordinating gaps mounted on a transformer*

If these sparkover voltages are plotted against time a volt-time curve is obtained as shown in Fig. 9.

Typical volt-time curves for a rod gap are shown in Fig. 10 and it will be seen that the gap has a higher flashover voltage on negative impulses. This disparity between the positive and negative flashover values is influenced by proximity to earth or to a conductor carrying current, *e.g.* a bushing.

A typical co-ordinating gap is shown in Fig. 11 ; rod electrodes are used, as although spheres have a shorter time lag their performance is adversely affected by any burning from the power arc which follows a sparkover and by climatic conditions.

Support (or Post) Insulators

Typical positive and negative impulse curves for a multi-unit post insulator are shown in Fig. 12.

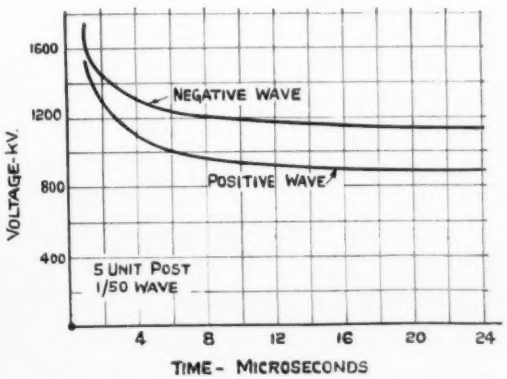


Fig. 12. *Impulse breakdown characteristics of post insulators*

As would be expected, the curves are generally similar in form to those of a rod gap.

Suspension and Tension Insulators

Typical curves for a multi-unit insulator string are shown in Fig. 13. It will be noted that the addition of arcing fittings and the consequent change in configuration of the electric field has, in this case, resulted in a change in the relative positions of the positive and negative volt-time curves.

Transformers

In addition to the previous items which concern flashover in air, the impulse characteristics of

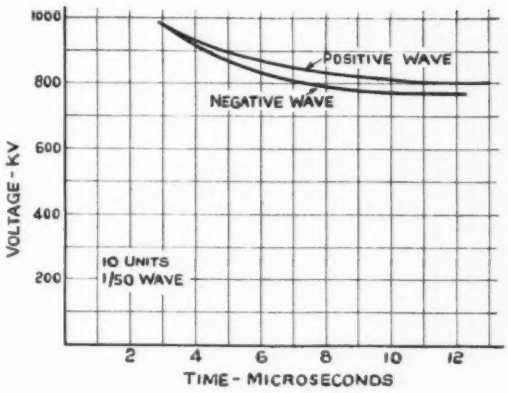


Fig. 13. *Impulse breakdown characteristics of suspension insulators*

transformers are important. The insulating materials used in high-voltage transformers are oil and paper, and a typical withstand volt-time curve of transformer major insulation is shown in Fig. 14. It will be seen that it differs from previous curves in showing a voltage which is less affected by time, being substantially flat after 5 microseconds.

In connection with the impulse characteristics of transformers it should be borne in mind that impulse voltages stress the inter-turn insulation of the transformer as well as the insulation to earth. The inter-turn stress depends on the steepness of the wave front of the impulse and may be aggravated by oscillations occurring within the transformer winding. The protection of the inter-turn insulation is, however, primarily a matter for the transformer designer rather than for the system engineer, and a number of ingenious designs of winding have been evolved.[1]

Expulsion Gaps

The simplest form of expulsion gap (protector tube) consists of a single air gap within a fibre cylinder open at its lower end. The upper electrode consists of a metal cap with a rod projecting into the tube, while the lower earthed electrode is in the form of a ring. When the gap flashes over, the power ' follow ' current arc causes gas to be evolved

1 *The type developed by The English Electric Company is described in the paper 'Design of power transformers to withstand surges due to lightning, with special reference to a new type of winding', by Chadwick, Ferguson, Ryder and Stearn. Proc. I.E.E. (1950) Vol. 97 Part II, p. 737.*

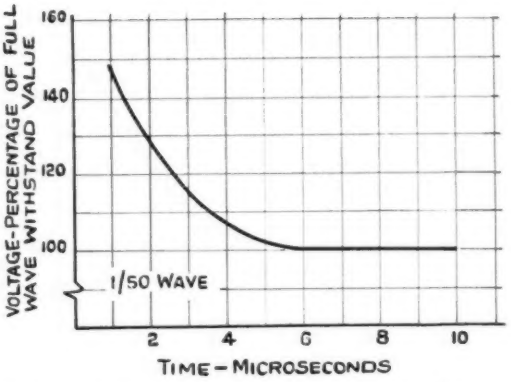


Fig. 14. *Impulse withstand characteristics of transformer major insulation*

from the inner wall of the tube and the pressure built up blows the arc out through the open end of the tube.

When used for line protection the expulsion tube is spaced from the line conductor to provide an external air gap. For transformer protection on the lower voltages the external gap may form part of the construction of the device.

The impulse characteristics of an expulsion gap are similar to those of a simple rod gap. It has the advantage that within a limited power follow current range the gap is self-extinguishing, but outside this range the device will fail and its application is therefore restricted.

Surge Diverters

In essence a surge diverter (lightning arrester) consists of a spark gap in series with a resistor made of a material which has a resistance inversely proportional to a given power of the applied voltage. At each surge diverter installation on a three-phase system three diverters would be used, one connected between each phase and earth (Fig. 15).

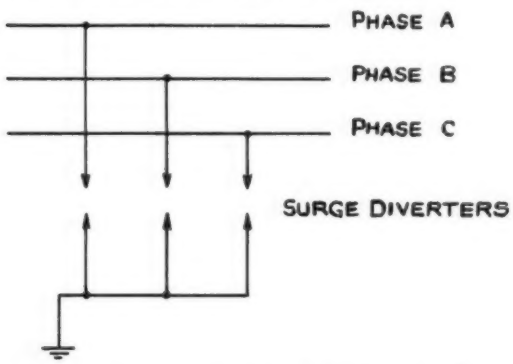


Fig. 15. *Arrangement of surge diverters on a three-phase circuit*

The spark gap element, comprising a multi-gap assembly, is included in the surge diverter to isolate the resistance element from the normal line voltage, since the resistor is very short-time rated and is not capable of having the line/earth voltage impressed across it for more than a cycle or two without failure. It is therefore necessary to ensure that the gap does not spark over under the maximum system-frequency line/earth voltage. At the same time it is desirable to keep the flashover voltage of the spark gaps as low as possible in order to provide the maximum protection for the apparatus. As a compromise between these conflicting requirements the impulse sparkover voltage is made about two to three times the peak of the power-frequency voltage rating of the arrester. The gap is so designed that its flashover voltage is very little affected by wave shape (Fig. 16) or polarity.

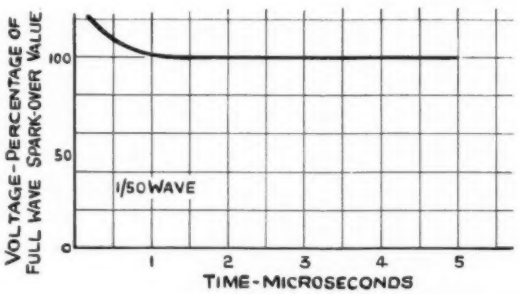


Fig. 16. *Impulse breakdown characteristics of surge diverter spark gaps*

The resistance element in the surge diverter generally consists of an assembly of blocks made up of silicon carbide crystals and a binder ; these blocks are similar in appearance and somewhat similar in composition to a small grinding wheel. The silicon carbide has the characteristic that its resistance is inversely proportional to about the fifth power of the current passed, and it also has a high negative temperature co-efficient so that as

the current is increased the resistance decreases rapidly. Consequently the voltage across the diverter is relatively independent of the magnitude of the surge. Fig. 17 shows a typical discharge voltage curve for 10/20 microsecond wave discharge currents. Owing to the non-linear volt-ampere characteristic of the valve-type surge diverter the wave shape of the discharge current is distorted from that of the applied voltage and a 10/20 current wave has been adopted as a standard corresponding to a 1/50 voltage wave.

Under normal working conditions the gaps hold the power-frequency voltage off the resistance elements, but when a surge of sufficient magnitude is applied the gaps sparkover and the surge is discharged to earth through the resistance elements. When the surge has been discharged the resistance elements will increase in resistance because the voltage impressed across them is the relatively low power-frequency voltage. The normal-frequency 'follow' current is thus reduced to a low value and at the first current zero the arc in the spark gap assembly goes out since there is insufficient current to sustain it.

Earth Wires

Lightning surges on an overhead network may be caused by direct or indirect strokes. Most direct strokes to a phase conductor of a line will cause flashover on account of the high stroke

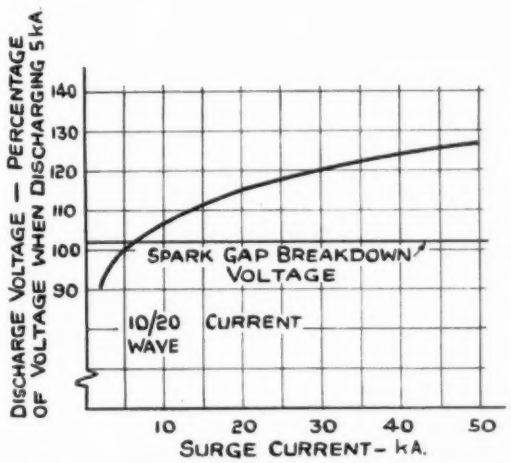


Fig. 17. Discharge characteristic of surge diverter

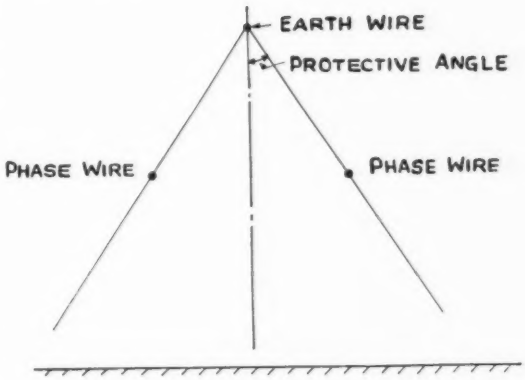


Fig. 18. Protective angle of earth wire

current and ' surge impedance ' of the line. An average value of the surge impedance ($Z = \sqrt{L \div C}$) may be taken as about 400 ohms for an overhead line conductor and 50 ohms for a cable.

It should be noted that when a direct stroke causes flashover of one phase conductor of a line, overvoltages are induced in the other phase conductors and can result in the operation of gaps or surge diverters.

Shielding by overhead earth (ground) wires is used on transmission lines, and by earth wires or masts in outdoor substations, to protect against direct strokes. While the protection given depends on the position of the earth wires and effectiveness of the earthing, as well as such factors as cloud height and the nature of the terrain, it is common practice to assume a ' protected zone ' in the form of a triangle with the earth wire at the apex, as shown in Fig. 18. A protective angle of 45 degrees represents average use for a single earth wire, while an angle of 60 degrees may be used where more than one wire is provided. As an indication, a single earth wire with a protective angle of 45 degrees has been estimated to give about 99.9% protection.

If a structure or earth wire receives a direct stroke it is raised to a high voltage above that of the phase conductors, which are substantially at earth potential relative to the stroke voltage, due to the voltage drop resulting from the passage of the surge current. This can result in a ' back ' flashover from structure to conductor and give rise to a steep wave front on the conductor. Earth wires must

therefore be sufficiently spaced from phase conductors, and structures and line towers efficiently earthed. Where earth resistivity is high, buried earth wires (counterpoises) may be used to reduce tower footing resistances.

While indirect strokes to earth near the line or substation induce transient overvoltages on phase conductors, flashover from this cause is in general confined to distribution systems of 33 kV and below.

Selection of Insulation Levels and Co-ordination

For a given application the impulse 'withstand' level (basic insulation level) of the station as a whole may be selected from one of the standard values given in Table I. This represents a minimum withstand level for the various items of equipment. Satisfactory co-ordination is then obtained if the protective devices prevent voltages in excess of this withstand level reaching equipment which may be damaged by such overvoltages.

The selection of insulation level and co-ordination may require consideration of a number of factors.

HIGHEST SYSTEM VOLTAGE

Insulation is more correctly related to the 'highest system voltage' than to the nominal voltage of a system. The highest system voltage is defined as the highest phase/phase R.M.S. voltage which is sustained under normal operating conditions at any time at any point on the system. It excludes voltage variation due to a fault condition or to the sudden disconnection of large loads.

In British Standard 77 : 1947 ('Voltages for A.C. Transmission and Distribution Systems') a maximum operating voltage of 10% above nominal voltage is specified. The Swedish standards permit a maximum voltage 15% above the nominal and in the United States of America the difference is 5%. Special consideration is necessary when the highest system-voltage exceeds this permissible maximum value.

SURGE DIVERTER RATING

Surge diverters are rated on maximum R.M.S. line/earth voltage, and standard surge diverter ratings take into account the permissible system-voltage variation referred to under the previous heading. Selection is normally based on the assumption that in service the 'highest system-voltage' is only exceeded under very abnormal operating conditions, and on the improbability of a diverter operation coinciding with a voltage exceeding the highest system voltage. If, owing to special circumstances, abnormal system voltages[2] are likely to be frequent, and diverter operations are likely to take place during such conditions, then it may be necessary to use a diverter of a higher voltage rating. The selection of a surge diverter depends on whether the system is non-effectively or effectively earthed. In the latter case the maximum line/earth voltage under fault conditions does not exceed 80% of the highest system-voltage, and a diverter of reduced voltage rating commonly known as 'an 80% diverter' is used, permitting a reduced insulation level. The requirement of a maximum line/earth voltage not in excess of 80% of the highest system voltage is generally met in practice if for all conditions of operation the ratio of zero sequence reactance to positive sequence reactance is positive and less than three, and the ratio of zero sequence resistance to positive sequence reactance is positive and less than one.

The protection given by a surge diverter is dependent on its discharge voltage characteristics (Fig. 17) and on the method of connection to the apparatus, usually a transformer, to be protected. To determine the protection level a margin above the diverter discharge voltage should be allowed to meet such factors as surge currents of a magnitude and steepness in excess of those prescribed. In America, for high-voltage substation application, a factor of 1.15 times the diverter voltage when discharging a 5,000-amp 10/20 wave has been advocated and, unless the diverter is mounted directly on the transformer, a constant 30 kV should be added for voltage drop in the diverter lead and earth. The level so determined should not exceed the withstand level of the protected equipment.

The selection of a 5,000-amp discharge current is based on statistical records of surge diverter lightning discharge currents in service. On occasions diverters may also operate on low-current long-time switching surges ; while modern diverters meet normal service conditions, unnecessarily frequent operation is to be avoided.

2 See 'System-frequency Overvoltages' on page 120.

Where equipment is connected directly to a line without overhead earth wires, as for example at a fused tee-off point, high values of discharge currents through diverters are possible. In these circumstances co-ordination should be based on a diverter discharge current of 20 kA, but no allowance need be made for voltage drop in the diverter lead since the diverter will be very close to the apparatus protected. In general such considerations will apply only below 66 kV since it is only at these voltages that overhead earth wires are commonly omitted.

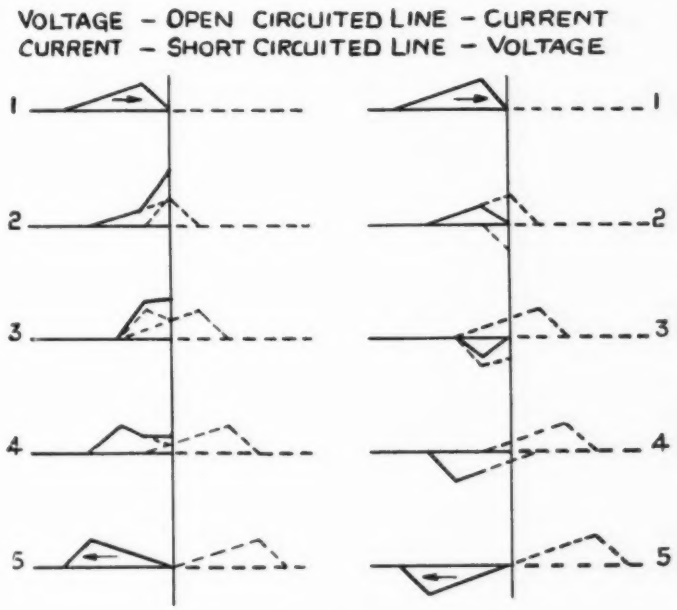


Fig. 19. *Reflection of travelling waves*

Surge Diverter Location

A surge diverter serves to reduce the voltage to a minimum only directly across its terminals. Since the most costly items in a station are the power-transformers, which if damaged involve lengthy interruption of supply, the diverters should be located as near to the transformers as practicable. Economic and layout considerations, however, may dictate the location of the diverters elsewhere in the station.

The waves of current and voltage resulting from a lightning stroke travel along an overhead line at approximately 1,000 feet per microsecond, and in cables at about 600 feet per microsecond; in travelling they are attenuated and distorted, the wave fronts becoming less steep. If a wave encounters a change in surge impedance, reflection occurs, the reflected wave being equal to the wave transmitted beyond 'the point of discontinuity' minus the incident wave. If a higher impedance is encountered the reflected voltage wave is of positive polarity with respect to the incident wave, and the reflected current wave of negative polarity, while if a lower impedance is met the reflected voltage wave is negative and the reflected current wave is positive. In the extremes, at the open end of a long line the voltage is doubled and the current reduced to zero, while at a point of short-circuit the voltage is reduced to zero and the current doubled (Fig. 19).

When a voltage wave entering a station reaches a surge diverter the voltage at this point is reduced to that of the diverter discharge voltage and at the same time a negative reflected voltage wave travels back over the line. The reduced voltage wave travels onward from the diverter until it reaches the transformer where positive reflection takes place. The voltage at any point on either side of the diverter is, for any instant, obtained by superimposing the appropriate reflected and incident waves at that point ; the nearer the point to the diverter the closer will the voltage approach that of the diverter.

While a surge diverter gives protection in both directions, the greater the distance from the diverter the less effective is the protection, and as an approximate rule the following distances should not be exceeded :—

Insulation Level applicable to:—	Diverter rating	Distance in Feet equal to:—
Non-effectively earthed system ..	80%	kV of system.

Non-effectively earthed system ..	100%	kV of system divided by 2.
Effectively earthed system	80%	kV of system divided by 2.

Shielding

To avoid very steep-fronted high-current surges resulting from direct lightning strokes in the immediate vicinity of a station, the lines radiating from the station should be shielded, and to take advantage of the effect of attenuation and distortion the earth wires should extend for at least a half mile. The effectiveness of such earth wires is dependent upon tower footing resistance, which should be kept as low as practicable. In localities where lightning is prevalent, shielding should also be provided above the station itself.

Rod Gaps

In areas of low isoceraunic level, such as Great Britain, rod gaps are commonly used in place of surge diverters, for economy. Separate co-ordinating gaps mounted on or near the transformer may be provided, or suitable rod gaps may be used on the transformer bushings. While it is claimed for the separate co-ordinating gap that it may be so mounted as to keep the arc on flashover clear of all other equipment, a bushing gap has the advantage that the divergence between the positive and negative impulse sparkover voltages can be reduced by suitably locating the gap with respect to the bushing.

To provide a margin of safety, gaps used for co-ordination are normally set to have a 50% impulse flashover voltage of about 80% of the transformer impulse withstand level, and it is the general practice of The English Electric Company, on outdoor bushings used for transformers, to provide rod gaps with settings in accordance with Table II.

Table II

Impulse Withstand Level kV	Gap Setting inches
200	7
250	8
350	13
450	17
550	22
650	26
800	31.5
1,050	45

It may sometimes be found desirable to use somewhat increased gap settings in order to avoid flashovers due to switching surges, but in so doing some loss of protection may result. In this connection it may be noted that on the 132 kV grid system, using transformers of 550 kV impulse level, the British Electricity Authority uses 26-inch co-ordinating gaps. Where surge diverters are used, the gaps provided on the transformer bushings for co-ordinating purposes may be retained as ' back-up ' protection.

Gaps may also be provided on the switchgear in a station, for example on circuit-breaker bushings and isolating switch insulators. These gaps have appreciably higher settings than the co-ordinating gaps and their primary purpose is to act as arcing horns to protect the insulators from damage by power arcs in the event of flashover. On the British Electricity Authority's 132 kV grid system the arcing horns on the switchgear have 39-inch gap settings.

For the higher voltages, rods or rings may also be provided as stress control to suppress corona.

Since flashover of a protective gap results in an earth fault which can only be cleared by de-energising the particular circuit, some consideration may be given to the limited application of surge diverters to selected circuits ; a case in point might be a generator transformer circuit in a major power station.

Reduced Insulation Level

The cost of high-voltage equipment is very considerable and of this cost insulation represents a large proportion. Any method by which the amount of insulation may be reduced is therefore of great economic benefit.

As mentioned on page 121, the internally generated over-voltages on an effectively earthed system are considerably less than those on a system earthed through significant amounts of resistance or reactance. Consequently, if a system is effectively earthed the insulation may be somewhat reduced. Further, as explained under ' Surge Diverter Rating ' on page 130, diverters of reduced voltage rating may be used on an effectively earthed

system ; these have a lower discharge voltage than diverters of full voltage rating, and permit the use of a lower insulation level on the protected apparatus.

For transformers it is financially advantageous to reduce the insulation level of equipment to be used on system voltages of 88 kV and above ; even below this voltage, graded insulation may be desirable to reduce costs. For switchgear there is no advantage in the use of reduced insulation levels for system voltages below 110 kV, and even at this voltage the advantage is very small ; it is doubtful if the use of a reduced insulation level for circuit-breakers is really justified below 165 kV.

In the range from 88 kV to 165 kV it is common practice to use full insulation level on all apparatus apart from the transformers and to reduce the insulation level of the latter. The higher impulse level on the switchgear and busbars somewhat reduces the likelihood of failure on items of equipment common to a number of circuits ; the transformer, at the lower impulse level, has the surge diverters or protective gaps mounted close to it and particularly intended to protect it, and so is the best protected item of equipment.

Where a reduced insulation level is used, the usual practice is to adopt the next lower insulation level. For example, a 132 kV transformer with reduced insulation level would have a 550 kV impulse level, corresponding to 110 kV full insulation level, instead of 630 kV (Table I).

At 165 kV and above it is the general practice on effectively earthed systems to use a reduced insulation level on all apparatus, since at these high voltages it is thereby possible to effect substantial savings on all items of equipment.

Station Clearances

While many individual pieces of apparatus are now impulse tested as a type test, it is necessary when designing a station to have some ready method of deciding the air clearances between connections and structures etc. which cannot, of course, be impulse tested. The electrodes bounding these clearance spaces may approximate to parallel bars, rod gaps or any other arbitrary configuration, so that in setting a clearance distance account should be taken of the worst possible configuration unless alleviating circumstances are present.

Clearances normally used by The English Electric Company are given in Table III. Somewhat reduced clearances may be justified on economic grounds where the incidence of lightning is low.

Table III

Phase/Earth Clearances for Busbars and Connections

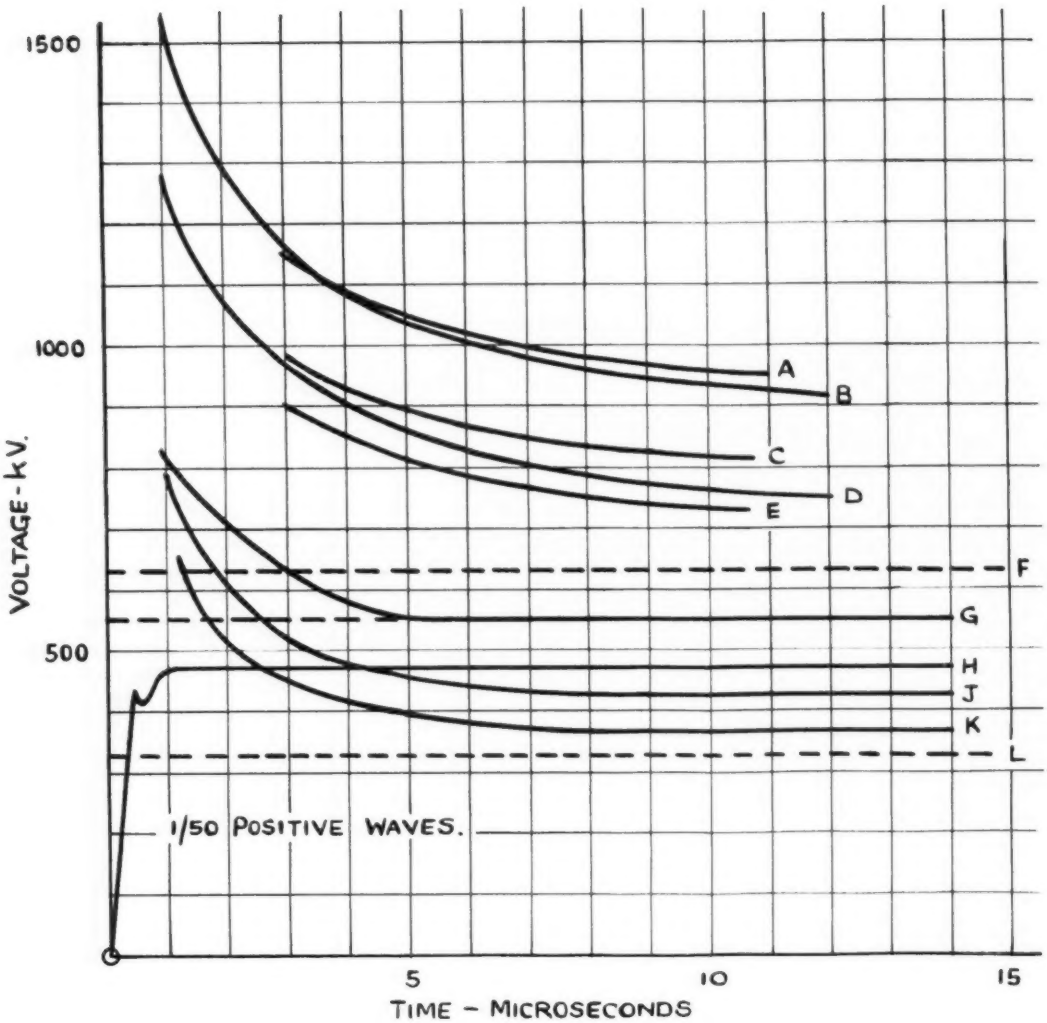
Impulse Withstand Level kV	Minimum Clearance to Earth in Air inches
190 to 200	16
260 to 275	22
330 to 350	30
450	39
550	48
630 to 650	54
730 to 750	66
800	69
890 to 900	75
1,050	84

Other Considerations

In choosing the insulation to be used on outdoor equipment two other factors are of importance ; they are the effects of pollution and altitude.

Pollution

Normal designs of outdoor equipment are intended for use under the usual conditions of atmospheric pollution, but where the pollution is unusually severe extra precautions must be taken. Because of the electric field surrounding an insulator, particles which may be present in the atmosphere are attracted and may form an adherent coating on the insulator surface. Under dry conditions these deposits may be of no significance but when they are damp they tend to form conducting paths and predispose the insulator to flash over. In Britain the average deposit from the atmosphere, mainly soot, tar and ash from coal fires, amounts to 90 tons per square mile per year and in heavily polluted districts may be from 250 to 600 tons per square mile per year. These quantities of deposit are bad enough but in Britain we have very few heavy rain-storms to help to wash the insulators, most of the rain falling in light showers which only damp the surfaces. Pollution troubles may result from chemical fumes, fog and salt spray from the sea.



A Tension and suspension insulators — 12 units
B Post insulators — 5 units
C Tension and suspension insulators — 10 units
D Post insulators — 4 units
E Tension and suspension insulators — 9 units
F 630 kV level
G Transformer withstand impulse level
H 121 kV surge diverter
J 26-inch rod gap
K 22-inch rod gap
L Peak value of three times phase/neutral voltage

Fig. 20. *Insulation co-ordination for a* 132 *kV station*

So far no artificial methods of reproducing the effects of pollution have been found sufficiently satisfactory to form the basis of a test, and the normal wet-test with clean insulator surfaces is not a reliable indication of the performance of the insulator when dirty ; the specification of the minimum creepage distance has proved the best solution. A creepage distance to earth of 0.67 in/kV of system voltage, *e.g.* 88 in. for a 132 kV system, has been found satisfactory for conditions of normal pollution, and 1 in/kV of system voltage where pollution is heavy. In the latter case at least half the specified creepage distance should be protected against rain at right angles to the axis of the insulator. These figures are in accordance with British Standard 116 : 1952.

ALTITUDE

Switchgear and transformers to British Standards are suitable for use at altitudes not exceeding 3,300 feet above sea level.

The effect of high altitude is to lower the air flashover voltage compared with that at sea level, while puncture and oil flashover are unaffected. It is specified that where the above altitude is exceeded the insulation level of parts in air shall be selected by increasing the standard impulse withstand voltage (and normal-frequency wet withstand voltage) by 3.5% for each 1,000 feet in excess of 3,300 feet above sea level.

Similar consideration must be given to the choice of air gap settings for use at high altitudes.

Standard surge diverters are designed for use at altitudes not exceeding 6,000 feet. The probability of use above this level is small and in such an event reference should be made to the manufacturer of the particular diverter.

Example of Co-ordination

To bring together the various points mentioned in the preceding sections an example is now given of the co-ordination of the insulation in a typical 132 kV station on an effectively earthed system having transformers of 550 kV impulse withstand level and the other apparatus of 630 kV level. It is assumed that the altitude is below 3,300 feet and that the pollution is not unduly heavy. The positive volt/time curves for the various devices have been plotted in Fig. 20 to demonstrate the co-ordination which can be obtained ; normally it is not necessary to plot curves in this way since a simple tabulation of the figures is usually adequate.

For the protection of the transformers and other equipment either a surge diverter or a rod gap may be used. Since this is an effectively earthed system an '80% diverter' would be used, that is, one rated 121 kV. This particular diverter has a maximum discharge voltage of 444 kV when discharging a 5,000-amp surge, and calculating as under 'Surge Diverter Rating' on page 130 gives:—

$$(1.15 \times 444) + 30 = 540 \text{ kV}.$$

This is below the transformer withstand level of 550 kV, assuming that the diverter is located within about 60 feet of the transformer terminals.

If a rod gap is to be used for protection, Table II gives a value of 22 inches for a 550 kV impulse level transformer, and in Fig. 20 it will be seen that this gap gives protection to the transformer even for waves as short as one microsecond. There is, however, only 25 kV margin between the 50% flashover value and the value of three times the normal line/neutral crest voltage mentioned under 'Internally Generated Overvoltages' on page 121 as the possible value of switching surges. Thus, an occasional flashover of the rod gap on an abnormal switching surge is possible. If the gap is increased to 26 inches to reduce this possibility, Fig. 20 shows that adequate protection is not afforded to the transformer for very steep waves. The choice between these two values is one requiring engineering judgment in individual cases and the consideration of other factors ; for example, the presence of overhead earth wires on incoming lines will greatly reduce the probability of steep fronted waves reaching apparatus.

It will be seen that a four-unit post insulator of the type having the characteristics of Curve D in Fig. 20 will be adequate to meet the required impulse level of 630 kV. It has a creepage length of 119 inches, of which 85 inches is protected. Since an area is being considered where pollution is not serious, the four-unit post will suffice. In an area of heavy pollution, where 132 inches creepage length is required, five units would be necessary to give adequate creepage distance even though four would meet impulse requirements.

A similar state of affairs exists in regard to tension and suspension strings of 'cap and pin' insulators. From Curve E in Fig. 20 it will be seen

that nine units meet the impulse requirements but the creepage distance is only 110 inches, of which 74 inches are protected. To provide more margin for creepage, ten units would probably be used for suspension strings, giving 122 inches total creepage length with 82 inches protected. For the tension strings, which having their axes more or less horizontal are more affected by rain, an additional one or two discs would be used.

The clearance to be used between live parts and earth in those parts of the station not subjected to impulse tests will be 54 inches in accordance with Table III.

It has sometimes been suggested that a large number of insulation levels should be used, with the highest level for busbar insulation and grading down to the lowest level at the transformers, but practically this is not economical since the various categories of equipment have different impulse characteristics, making close grading for waves of differing wave front impossible.

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